# South African Journal *of* Science

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Increased risk of heat stress conditions during 2022 Comrades Marathon

Sgr A* and southern Africa's geographic advantage in future tests of gravity

Cultivation – a tool for conservation and commercialisation of medicinal plants

Bamboo as a potential construction technology in South Africa

Nitrogen isotopes confirm sewage as pollution source in Hartbeespoort Reservoir

Electrification of minibus taxis in the shadow of loadshedding


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## Research Articles



## Research Letter



## Corrigenda



**Cover caption**
The Comrades Marathon is South Africa's most recognised and largest ultramarathon event. The race will be held later in the year – in August – in 2022 than in previous years. In their paper on page 103, Havenga and colleagues show that the later date will increase the risk of heat stress conditions for the runners.

# Habitable and sustainable worlds

On 14 July 2022, the Academy of Science of South Africa (ASSAf) hosted its 8th Presidential Roundtable discussion, with Prof. Jonathan Jansen as the chair, and with Prof Mary Scholes, Ms Alize le Roux and Mr Matthew Hemming as speakers. The topic was 'The Human Costs of Climate Change'. The event was a model of good science communication – clear, sober analyses backed up by evidence, presented in an accessible and understandable way and with no unnecessary use of jargon. The messages were compelling and clear, and a recording of the event (available here) should prove helpful to anybody wishing to share information on this important topic.

For the *South African Journal of Science*, the event is noteworthy in at least three ways. First, the topic is one of existential concern to all who share our planet. Second, the science was communicated accessibly and clearly, and not just for a niche audience. Third, the meeting demonstrated the importance of working together across disciplinary lines to begin to address difficult problems. Our Journal is a mouthpiece for science on our continent, but it is also committed to transdisciplinarity, clear communication across boundaries, and working together to solve big and difficult problems.

Our most recent special issue, on COVID-19, explicitly sought this kind of interdisciplinarity to approach the difficult question of understanding and managing a pandemic in low-resource contexts, and a forthcoming special issue, similarly, will examine, from perspectives ranging from engineering to the social sciences, how what is commonly thought of as waste can be a resource in a different kind of economy. But over and above these explicit and planned efforts to encourage communicating and working together across divides, it is pleasing to see the extent to which regular contributions to the Journal, singly and collectively, strengthen the overall messages central to a journal like ours.

In a review essay, the disability studies scholar Rosemarie Garland-Thomson[1] cites (p. 301) the work of Nancy Mairs[2], declaring that her task in writing about living with multiple sclerosis is 'to conceptualize not merely a habitable body but a habitable world: a world that wants me in it'. In referring to this world, both Mairs and Garland-Thomson are alluding to a world which excludes people on the basis of bodily difference; they both hope for a world which accommodates and caters for us all. There are, though, of course, many other ways in which a world can exclude and not be habitable for everyone. There are exclusions on the basis of any number of social markers, including race, gender, and age, and there are exclusions on the basis of physical habitability – the inaccessibility of the built environment, and the destruction of the planet in what has come to be referred to as the Anthropocene. The ASSAf Roundtable amply demonstrated the impact of climate change on where, and under what conditions, members of our species and others may or may not be able to inhabit parts of (and ultimately all of) the planet on which we live.

Many articles in the current issue of our Journal demonstrate the contribution of human and environmental factors in creating a world that is difficult to inhabit optimally. In their Commentary, Booysen and colleagues outline both the problem of the energy demands and environmental impact of minibus taxis and the ways in which electrification, including the use of solar energy, may go some way to solving the problem. The minibus taxi industry in Africa is, of course, an ingenious but costly solution for a range of problems on our continent. The colonial and apartheid design of cities contributes to a situation in which people live far from where they work, the transport infrastructure is commonly inadequate, with huge backlogs in terms of rail and other networks, and the vehicles that are in use depend at this stage on fossil fuels. But as these authors show, large-scale systems and design thinking, and harnessing of local renewable resources may suggest a way forward.

A number of other items in this issue address environmental issues in similarly innovative ways (see, for example, the contributions from Windapo et al., Chidi et al., Adlam et al., Dhansay et al., Welz et al., as well as others in this issue). Clearly, thinking for the future requires reassessing and innovating in the fields of education and training as well, as discussed by Boughey in her Book Review. It also requires openness to rethinking how we value and reward research and research careers. In his provocative Perspective, Glenn suggests that current approaches to rewarding research in South Africa (he focuses on the NRF rating system but his comments have wider implications) may be lacking. He cites anecdotes, which certainly resonate with many conversations within the academy in South Africa and more broadly, in which ambitious new researchers are encouraged to specialise as narrowly as they can in their work. Hyper-specialisation (the academic equivalent of the production of monocultures) is commonly rewarded and valued, with global expertise in a highly specialist field being the implicit marker of an excellent scientist. In my experience, though there is much lip service given to working across boundaries, to collaborating and to constantly starting from scratch as researchers discover and create new fields of endeavour, the allure and prestige of hyper-specialisation remain. I do not wish to imply that we do not need specialists – we do. But in order to address complex problems, we need more than this. We also need boundary-spanners and rule-breakers, researchers open to learning different ways of thinking and doing science.

The issues of climate change and habitat destruction are existential for all of us. In order to address these issues, we need to think not only about how to collaborate in innovative ways but also about what we value in the research world and how we train future generations of scholars. At our Journal, we address questions of sustaining and diversifying the academy through training and support for new academic writers, and through mentorships. But these are small contributions. We want our Journal to be part of the conversation about the histories of the sciences and professions on our continent (and Limebeer and Dwolatzky address this in their Commentary), and also, crucially, about how we go forward so that future generations are better than we have been at making the world more habitable.

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# Postgraduate education in a globalised world

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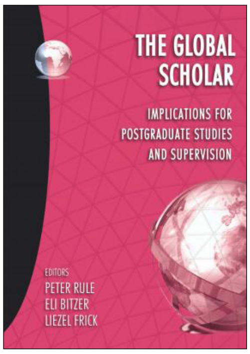
The global scholar: Implications for postgraduate studies and supervision

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Interest in postgraduate education and the supervision of postgraduate research has developed in recent years, largely as a result of the impact of the so-called 'knowledge economy'. South Africa's National Plan 2030[1] draws on globalised discourses in holding that increases in the number of graduates, particularly at doctoral level, will contribute to economic prosperity because of the potential of postgraduate education to contribute to the processes of reinvention that drive the economic system itself. Even a brief glance at the mission and vision statements of a small sample of universities shows how this idea has been taken up within the higher education sector. In the context of high levels of unemployment, the idea that a postgraduate degree can lead to better work prospects also means that students who might never have considered doing a postgraduate degree previously, have now come forward to study at this level. All this then means that academics are being called upon to take on heavier supervision loads with a diverse array of students.

This collection of essays edited by Peter Rule, Eli Bitzer and Liezel Frick, stems from the 2019 Biennial International Postgraduate Supervision conference hosted by Stellenbosch University. Given the title of the book, and the interest in postgraduate education across the world because of the ideas noted above, it is fitting that the authors included in the collection should represent a cross-section of scholars from places as diverse as the USA, Australia, Israel and various countries in Europe. This does not mean that South African work is neglected, as contributions from a number of scholars who are known in this country for their interest in postgraduate education show.

A comment by the editors (p.2) that globalisation can be understood 'in both utopian and dystopian terms: celebrated by some for its opportunities and affordances, and repudiated by others for its destructive cultural and ecological impacts' captures the breadth of the collection. McKenna's critique of human capital theory[2-4] and her posing of the question 'Who is served by postgraduate education?' is firmly located at the more critical end of the continuum of responses to globalisation. For McKenna, asking this question spotlights, not only issues related to differentiated access and success in the South African system, but also the need for postgraduate research which aims to contribute to the good of society and the planet, and which is not simply aimed at driving economic development and benefitting individuals. The troubling of discourses currently dominating higher education offered by McKenna will resonate with many readers of this Journal and offer challenging insights to others who may unwittingly subscribe to them.

A number of chapters look at more positive aspects of globalisation with one, by Morozov and Guerin, exploring the mobility it has promoted amongst both academics and students. In the context of the pandemic, which struck the year after the conference at which the paper on which the chapter is based was presented, the focus on digitised communication in supervision is particularly interesting. Morozov and Guerin's response to questions about whether remote supervision ultimately presents an attractive proposition or whether it results in a reduced learning experience is largely positive, although the chapter is written from a perspective in a country where access to devices, data and the Internet itself is much less problematic than in South Africa. Although postgraduate students tend to be better resourced in this regard, it is by no means the case that all have adequate access to devices and data or live in places with good connectivity. Also absent is the way disciplines impact on the possibility of studying from a distance and on what this might mean for practice. In the humanities, where one-on-one supervision is common, interaction with a group of fellow doctoral candidates in a campus setting can be critical to developing a broad knowledge base and seeing how cognate disciplines tackle similar problems and objects of interest. In the natural sciences, a lot of research is project based and models of supervision offer the opportunity of working in a team and learning alongside others at laboratory benches on a daily basis.

To my mind, however, one of the most significant papers in the collection is Clarence's attempt to develop a theoretical framework for exploring emotions in doctoral research. The phenomenon of 'imposter syndrome' (where candidates are captured by the idea that they are not 'good enough' to be doing doctoral research) will be familiar to many supervisors along with the way emotional and psychological problems can impede and, even, halt progress.

Significant in Clarence's chapter is the claim that conceptions of the ideal student as 'rational, objective, capable of reason and master of their emotions and thinking' (p.221) stem from ideas that first emerged in the Enlightenment of 17th- and 18th-century Europe. If this is the case, does it not mean that we need to consider that perceptions of behaviour we may consider 'inappropriate' are conditioned by the privileging of particular ways of being with their roots in another age on another continent? Is there not cause to understand some of what our students do and say as stemming from their 'being', from identities developed in very different contexts? Is there not space for pedagogies, however they may be conceptualised, that recognise and acknowledge difference and the way dominant beliefs about appropriate ways to 'be' and behave serve to exclude? Many of those calling for the decolonisation of our universities would answer that question with a resounding 'Yes'.

Regardless of where readers may stand on the ideas she prompts, Clarence's work is typical of the way essays in this collection provoke thought about postgraduate education and supervision. At a time when supervisors are being asked to do more, to take on an increased number of the diverse range of students who now present themselves for postgraduate study in a world confronted by the challenges of globalisation, time spent engaging with this collection produced by some of the best researchers on postgraduate study and supervision in the world will not disappoint.

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**BOOK TITLE:**
Fundamentals of tropical freshwater wetlands: From ecology to conservation management


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# Towards the conservation of wetlands in the tropics

All around the world, tropical wetlands provide many ecosystem services, as described by the Millennium Ecosystem Assessment in 2005.[1] The benefits include clean water, ensuring a stable water supply, and providing habitat to a wide variety of important species as wetlands are among the most biodiverse ecosystems on the planet. *Fundamentals of Tropical Freshwater Wetlands: From Ecology to Conservation Management,* edited by Tatenda Dalu and Ryan Wasserman, presents an informed and well-structured series of original studies around the topic of wetlands. The book comprehensively describes how wetlands are formed and their hydrology; climate and geomorphological factors; physiochemical dynamics; nutrient cycles and ecological theories; biotic components; and the management of wetlands. The two editors are well-established African research scientists in the field of aquatic ecology, and I applaud them for compiling this book and coordinating more than 70 esteemed and enthusiastic scientists from around the world who all did a great job in creating this solid output. The book is a pleasure to read; it is well paced, organised, and highly informative. The chapters are imaginatively named and framed in their main contexts. Overall, this book is a substantial contribution to wetland science and the contents will be of interest to students, resource managers, individuals and policymakers worldwide.

The book starts with an introductory chapter which gives a general overview of tropical wetlands as well as the chapters of the book. The introductory chapter shows how the rest of the chapters link to provide a smooth flow to the book. Although all the chapters are equally important, the chapter on the importance of policy in the conservation of wetlands (Chapter 22) is particularly noteworthy. This chapter provides examples of policies in different countries; for example, Zambia has a strict policy to manage wetlands which is backed by legislation, due to the value that wetlands in Zambia confer through providing mostly provisional services which are normally acknowledged in society (such as the provision of fish in the Barotse Floodplain). The chapter explains how discrepancies in policy between countries can affect the general protection of wetlands, especially for those that are shared between countries or that are linked to other regions. The editors have also included chapters on the value of wetlands in monetary terms (Chapters 19 and 22). Monetary value is important when advocating for the protection of wetlands, as environmental scientists and conservationists can quantify the economic benefits as well as losses to convince policymakers to provide legislation for their protection, especially in countries that have weak policies for the protection of wetlands. Several chapters highlight the threats to wetlands; these threats are global and include climate change, habitat destruction, and invasive species, among others – which are also amongst the major causes of global biodiversity losses.

A chapter on the recent technological advances in monitoring wetlands using Geographic Information Systems (GIS) is also included. GIS allows better remote viewing and understanding of wetland physical features and the relationships that influence a given critical environmental condition. The editors did well to include a chapter on the participation of indigenous people in the management of wetlands (Chapter 23). I view this chapter as one of the most important, as most indigenous people – especially in Africa – have lived around wetlands and have their own local management laws and beliefs that protect wetlands. Indigenous people are generally regarded as the custodians of natural systems. The authors emphasised the need for African governments to recognise these indigenous groups, as stated in Article 18 of the UN Declaration on the Rights of Indigenous Peoples.

The editors and authors also have done well to advertise the book on various social media platforms, which helps in disseminating information about wetlands. One drawback of the book, however, is its cost of USD150 (~ZAR2400) – a price which might be beyond the reach of many, especially those in tropical countries, many of which are still developing. The book, therefore, may be prohibitively costly to its most important audience. Affiliation with an institution which subscribes to Elsevier may help in accessing the book. The book's worth will be measured by the extent to which it is cited in the literature.

I encourage university libraries to buy the book and aquatic ecology lecturers and students to make use of it in their curricula/courses. If the editors and authors are able to engage environmental managers and policymakers and share summaries of the book with them (through workshops or presentations), it will go a long way in protecting wetlands and ensuring that the book is not merely an intellectual exercise.

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# Research ratings, research coherence and justifying the butterfly

**Significance:**
The South African National Research Foundation's insistence on research coherence and specialisation as major criteria in ratings exercises may be misjudged. Opportunistic and wide-ranging interdisciplinary research may be more important and more ethically justified in the Fourth Industrial Revolution.

*Even the aerobatic swift / Has not his flying-crooked gift.*

Robert Graves, 'Flying crooked'

*Float like a butterfly, sting like a bee.*

Muhammad Ali

## Introduction

A few years ago, a leading academic figure in my field shared, generously, insights into the ways in which the South African National Research Foundation (NRF) regarded research. We should not, she noted severely, behave like butterflies, flitting from one topic to another. The NRF wanted research coherence, proficiency in a field, persistence in establishing authority as specialists. Current NRF guidance on research ratings continues to note that 'unfocussed/opportunistic research' is not desirable and will lead to poor ratings or no ratings.

As a card-carrying contrarian, I argue that the obsession with coherence has led, and continues to lead, to bad effects: narrowness of focus, failure of interdisciplinary research, a failure to use the archive constructively, and a failure to respond to new challenges timeously. I want to justify the butterfly.

## Sociology of knowledge and the butterfly

This is not about the butterfly as an analogy where there is not much point in spending caterpillar years if one doesn't eventually fly – though that is a relevant point. A more helpful analogy would be one in which the butterfly turns into one of Karl Mannheim's *freischwebende Intelligenz,* the concept of unattached or free-floating intellectuals he took over from Max Weber.[1(III:4)] These were the people he hoped would rise above class interests, moving to produce a dynamic synthesis of social views. But butterflies aren't floating or just unattached so much as they are ranging and searching, driven by complex motives.

Another defence of the butterfly can be found in the work of French utopian thinker Charles Fourier, one of the founders of socialism.[2] For Fourier, the ultimate passion was the butterfly passion – the passion of variety he saw as necessary for a full life. Part of the NRF uneasiness with the butterfly seems to arise precisely from the puritan suspicion that butterflies enjoy their research too much.

Are butterflies a new manifestation of Isaiah Berlin's foxes who know lots of things as opposed to the hedgehog who knows (and presumably endlessly studies) one big thing?[3] Berlin's big distinction in his famous essay, however, was about those with 'a single central vision, one system' as opposed to 'those who pursue many ends, often unrelated and even contradictory… These last lead lives, perform acts and entertain ideas that are centrifugal rather than centripetal.'[3(p.2)] My interest here is less in the distinction between monists and pluralists – a distinction which seems increasingly dated – than in questions of method and focus. Nonetheless, in the spirit of Berlin's essay, let us oppose our butterflies to the NRF's virtuous termites, industriously, relentlessly, turning grass into a wonderful self-contained, hermetically sealed structure, and to the spider with a web that is constructed to trap passing prey.

My suspicion about coherence arises from a mix of factors, the latest being work on an NRF rating panel. Coherence here has either turned into people being or presenting themselves as super specialists with a narrow field, no doubt advised by dutiful research offices in universities which have internalised the NRF criteria. They say coherence, I mutter dull dog. And the fields are too often, in my biased view, trivial and marginal. But, of course, the more specialised and arcane, the more likely you will be to find a few favourable reviewers in the same area.

A second concern is that coherence can mean a resistance to finding out new material, to following interesting smells (good or bad) wafting from the archive or the news bulletins. The spider spinning its web or the termite mound reaching into the sky may be very impressive but what are they missing? What are the challenges that they are shaped to ignore?

I am not the only person noting the problems of the straitjacket of coherence and the problem goes beyond the humanities. Peter Thiel complains that innovations are slowing down.[4] Here is Derek Thompson in a recent *Atlantic* article exploring why science and innovation in the USA seem to be stagnating:

> *Today's scientists typically rely on grants from government agencies such as the National Institutes of Health and the National Science Foundation. This grant-writing process is so grueling that for many researchers it can account for up to 30 or 40 percent of their working hours. Although the NIH and the NSF are well-meaning organizations, they've*

> *created a very specific market for scientific research. Researchers are more likely to be funded if they can prove deep expertise, which has tipped the scales in favor of older scientists. Researchers are more likely to get funding if their proposals seem plausible to several members of the peer-review process, which encourages scientists to prove that the questions they're asking have sort of already been answered.*
>
> *When you put these market choices together – a bias toward older investigators over younger researchers, a preference for deep expertise over cross-disciplinary exploration, and an emphasis on plausible projects rather than radical ones – you get exactly what you bargained for. Today's scientists spend their time begging institutions for money to produce incremental science that clusters around a small set of seemingly safe ideas.*[5]

That seems to me as true in the humanities and social sciences, although the 'seemingly safe ideas' have a more tolerant range and wider partisan divisions.

Coherence derives from a time of clear disciplinary boundaries. We are living in the age of Harari's *Homo Deus* where artificial intelligence and new technologies make academics the latest endangered profession.[6] In the Fourth Industrial Revolution, our narcissistic certainty of our own purview of knowledge risks making us the equivalent of a London taxi driver investing years into The Knowledge in the era of satnavs. The great German media scholar Friedrich Kittler said 'Simple knowledge will do'[7] and that threatens to make redundant much of what has traditionally passed for training in one academic professional field. When we realise that we benefit from interdisciplinary work, we have to be willing to abandon some kinds of coherence to open ourselves to the new, to be opportunistic, and to seize opportunities.

The archive is another place where coherence and specialisation are threats as much as benefits. Assuming you know what you will find when you go into the archive is dangerous, maybe even deadly. If you emerge from archival work with the coherence you expected when you set out, or when you applied for funding, you are wearing very powerful blinkers, or rose or other coloured spectacles. Most important archival work involves pushing the researcher out of comfort zones and the already known and often demands new tools and help from people in related fields. The same thing could be said of much interview work or field research.

To understand what the butterfly may offer, let us return to the Robert Graves poem about the butterfly. This poem deserves recognition in a scientific journal, as all ornithologists no doubt immediately noticed, as it inspired Richard Brooke's name for the sub-species of Little Swift, *Apus affinis aerobates*. But what might the 'flying-crooked gift' of the butterfly be?

That flying-crooked seems to me to catch the tentative, exploratory, yet driven interests of the butterfly researcher. In the humanities, butterflies need a range of research skills and tools – linguistic, interpretive, theoretical – that differ in interesting ways from the termites and the spiders. Butterflies respond to things, to calls for papers, to new challenges, to complex problems and puzzles. When the COVID pandemic comes, they take the moral and intellectual challenge, the opportunity, in short, to see what academics can offer from their different perspectives. They change focus because the world has changed radically, whereas the NRF, it seems, would prefer people not to be distracted by events and lose focus and not to be 'opportunistic'.

Butterflies write interesting reviews. They are driven by a sense of injustice or unfairness and when this happens, they can switch, as Muhammad Ali bragged, and sting like a bee. They detect and pollinate. Building a termite mound doesn't give you much room to notice different kinds of injustice or unfairness, whereas the spider is set to catch a predictable prey in its web. The butterfly has a moral, contrarian, problem-solving orientation. At their best, butterflies become like Whitman's poet who 'judges not as a judge judges but as the sun falling around a helpless thing'. Or, perhaps, to becoming consulting cultural and social detectives interested in new crimes and new cases.

Berlin in his essay admitted that his distinction between hedgehog and fox was a simplification: 'Of course, like all over-simple classifications of this type, the dichotomy becomes, if pressed, artificial, scholastic and ultimately absurd'[3]. The same is clearly true here and the ideal scholars no doubt combine *sitzfleisch* and flightiness. But those who see butterflies as evanescent and lacking staying power may be wrong – good butterflies go on being curious and intrigued and flying crookedly longer. Charles Fourier was one of the pioneers of utopian socialism and his point about the butterfly or alternating passion was that change and diversity are important to the possibilities of a full life – and a full research life.

As for the NRF – how about some different criteria for research excitement and research importance rather than research coherence? Extra points to those who have collaborated with somebody outside their own discipline. Extra points for surprising archival discoveries that disrupt coherence. Extra points for responding to a new challenge with something unexpected. Extra points if you fall between disciplinary panels and disconcert those looking to find reviewers for you. And, particularly, extra points for being opportunistic and being willing to change focus.

## Competing interests

I have no competing interests to declare.

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# The first image of the Milky Way's central black hole and the unique enhancement Africa could offer future tests of gravity

**Significance:**

The Event Horizon Telescope (EHT) Collaboration recently released the first images of the supermassive black hole in the heart of the Milky Way galaxy. The ring size and shape in these images are consistent with Einstein's general theory of relativity. The location of this black hole in southern skies and its rapidly changing appearance mean that expanding the EHT into Africa is critical to optimally utilise this unique gravitational laboratory in the future. Leveraging our southern African geographic advantage will turn images into high-fidelity movies – a game-changing milestone for precision tests of gravity with the next-generation EHT.

## Introduction

Astronomers use a wide range of telescopes to study the universe, tuning into different parts of the electromagnetic spectrum to explore diverse astrophysical phenomena. Our eyes are sensitive to light that has a wavelength of approximately 500 nanometres. This is the region in which traditional, so-called 'optical' astronomy is carried out with facilities such as the Southern African Large Telescope in Sutherland. The choice of wavelength and telescope depends on the physical properties of the astronomical source of interest, e.g. hot gas at billion-degree temperatures is best studied at shorter wavelengths like X-rays. The recently launched James Webb Space Telescope will revolutionise our view of the infrared universe with a sensitivity significantly surpassing that of the Hubble Space Telescope. Another critical aspect of a telescope is the sharpness with which it can make out small details in a distant object. In this Commentary, we discuss a global network of radio telescopes known as the Event Horizon Telescope (EHT), observing light with a wavelength of 1 millimetre (mm), synthesising a much larger, earth-sized virtual telescope to achieve the sharpest detail attainable in astronomy. The primary objective of the EHT is to make images of supermassive black holes, behemoths that lie at the centres of galaxies and possess masses that range from about a million to ten billion times the mass of our own Sun.

## Very long baseline interferometry

The technique that enables this worldwide network of antennas to function is called radio interferometry. Its development won Martin Ryle the Nobel Prize in Physics in 1974 and it underpins the operation of the future Square Kilometre Array. The smallest structure a telescope can see, or 'resolve' in astronomical parlance, is known as its angular resolution $\theta$. It depends directly on the wavelength of light that is observed, $\lambda_{obs}$, and inversely on the telescope's diameter, $d_{tel}$:

$$\theta = \lambda_{obs}/d_{tel}.$$

The angular resolution can be made finer (enabling one to discern sharper details) by either decreasing $\lambda_{obs}$ or increasing $d_{tel}$. In practice, it is impractical from an engineering and cost perspective to increase $d_{tel}$ beyond a few hundred metres at most. To overcome this limitation, astronomers use the technique of interferometry in which signals from two or more elements (also referred to as antennas or stations), separated by a distance $D$, are combined according to the principle of interference of waves to achieve an effective angular resolution of $\lambda_{obs}/D$.[1] Such a synthesis of an 'aperture' (i.e. any element that collects light) of effective diameter $D$ is achieved by carrying out the observation for several hours, letting the rotation of the earth relative to the sky fill in the 'holes' or 'gaps' in this virtual telescope, in a process known as earth rotation aperture synthesis, devised by Martin Ryle and others in the 1950s.

In connected-element interferometry, the signals received by the individual stations are transferred almost instantly and combined coherently in real time. This is a significant challenge and expensive to achieve if the stations are separated by hundreds or thousands of kilometres. In such cases, temporal synchronisation is achieved using precise and independent atomic clocks that record the times of reception of the signals at the individual stations. This practice is known as very long baseline interferometry (VLBI).

The EHT is one such global VLBI network that operates at millimetre wavelengths to achieve an angular resolution that subtends 20 microarcseconds, which is approximately 100 million times smaller than the full moon's apparent diameter on the sky. At these short wavelengths, turbulent precipitable water vapour in the atmosphere absorbs and scrambles the incoming wavefronts of light.[1] Hence, millimetre-wave observatories are established at high-altitude sites with dry atmospheric conditions (Figure 1).

Also seen in Figure 1 is an example of the EHT digital backend which is present at every EHT station. After the electromagnetic waves are focused by individual antennas onto the cryo-cooled receivers, amplified, down-converted, filtered and digitised, the Petabytes of recorded digital signals are then transported to the two correlators in the USA and Germany. A correlator combines the signals from individual stations coherently and outputs the data in a format required by radio data processing algorithms. This completes the signal path in this virtual earth-sized telescope, enabling images of faraway black holes to be reconstructed. A notable aside is that each digital backend includes four Reconfigurable Open Access Computing Hardware (ROACH2)[2] boards, originally designed with significant involvement from South African engineers and the South African Radio Astronomy Observatory (formerly SKA Africa). The ROACH2 boards (which still bear the SKA Africa logo, Figure 1) are therefore a critical component in the EHT signal processing pipeline.

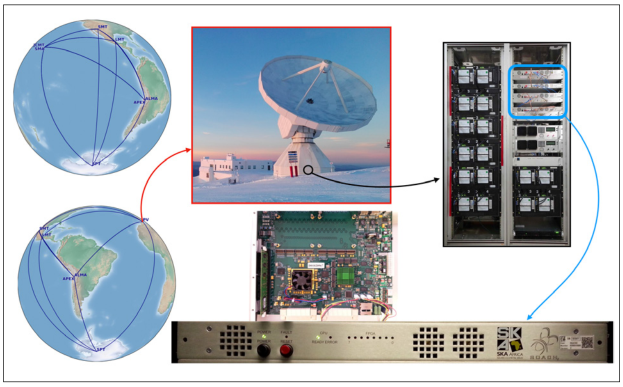


*Image credits: SARAO, IRAM, EHT Collaboration*

**Figure 1:** The 2017 EHT network as viewed from the centre of the Milky Way (left). The IRAM Pico Veleta 30-metre antenna in Spain (top middle), with the EHT VLBI backend deployed at all EHT stations (top right), which include South African developed ROACH2 digital backend boards (bottom).

## Sgr A* observations with the EHT

In April 2017, the EHT observed the supermassive black hole at the heart of the Milky Way, known as Sagittarius A* (Sgr A*) at a wavelength of 1.3 mm for five nights using eight telescopes situated at six geographical locations. These data were correlated at the Max Planck Institute for Radio Astronomy in Germany and the Haystack Observatory at the Massachusetts Institute of Technology in the USA. Following correlation, two calibration pipelines were deployed to correct for instrument imperfections and stabilise the signal to produce the data used for the remainder of the analysis.[3]

After five years of analysis, the first Sgr A* images were published in May 2022 (Figure 2).[4] The images are redolent of the images released by the EHT Collaboration in 2019 of the supermassive black hole at the centre of the galaxy M87 (M87*)[5], with a fiery ring surrounding a dark region corresponding to the shadow of the black hole. For both M87* and Sgr A*, the measured ring diameters on the sky agree remarkably well with predictions based on general relativity.

What causes the ring-like signature in these images? Hot ionised gas surrounding a black hole radiates as it orbits the black hole attracted by its immense gravitational pull. Any radiation that passes through the event horizon of a black hole, the boundary from which not even light can escape, is lost forever to the observable universe. Depending on the angle of approach of the light and the distance at which it passes the black hole, the curvature of the local spacetime bends its path around the black hole in different directions and to different extents. As a consequence, a region slightly larger than the event horizon at the centre appears dark, while the light bent around the black hole shines all around it, resembling a bright ring.

Though in theory any black hole surrounded by hot radiating plasma must be visible to the observer, even the nearest, most massive black holes cast exceedingly small shadows and rings on the sky, owing to their large distances from the earth. To image them with sufficient angular resolution required the assembly of the EHT.

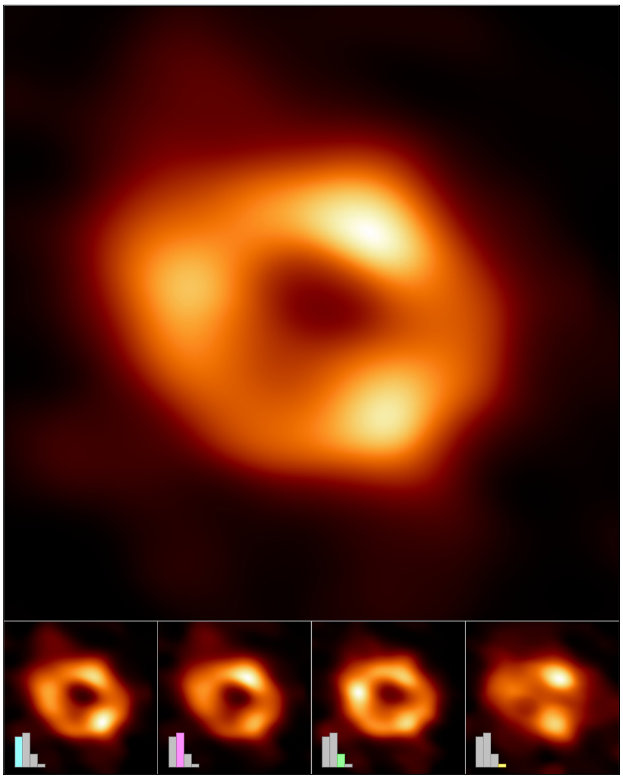
## Imaging challenges

Four methods were used to reconstruct images from the raw data output from the correlator. Thousands of images were created, all of which are consistent with the Sgr A* data.[6] Two of these methods are regularised maximum likelihood algorithms, conceptually different from the third, an implementation of the CLEAN algorithm used in radio astronomy for almost 50 years. The fourth is a cutting-edge, fully Bayesian imaging method that produces the full set of images that are consistent with the data.[7]

Compared with M87*, Sgr A* poses additional imaging challenges due to the fact that the source structure evolves rapidly. M87* is ~1500 times more massive than Sgr A* and light takes a few weeks to complete one orbit around M87* while it takes only a few minutes to orbit Sgr A*. This results in rapid variations in the observed source structure for Sgr A* on timescales of minutes, which violates a fundamental assumption made by conventional imaging methods in radio interferometry – that the source does not change during the observation. A completely novel approach had to be developed to account for the variability in order for these algorithms to work.[8]

Another significant challenge to imaging was the fact that Sgr A* is located at the heart of our own galaxy. Because the earth is located in the gaseous disk of the Milky Way, to observe the centre we have to peer through 27 000 light-years of gas and dust that constitute the interstellar medium. The free electrons in the interstellar medium along our line of sight to the Galactic Centre scatter the light from Sgr A*, causing the images to appear fuzzy and blurred. New theoretical and stochastic models of scattering were developed to mitigate these effects while imaging[6].

Optimising the four imaging methods to reconstruct the Sgr A* images required validation on synthetic data sets generated from known geometric models with the variability and scattering characteristics of actual EHT observations. An overwhelming majority of the final Sgr A* images obtained via this optimal imaging process display a prominent ring structure, with the ring size being consistent across imaging methods and parameters. The images were classified into four clusters or modes, with the first three modes comprising over 95% of the images displaying ring-like features, with a small fourth set showing non-ring morphologies (Figure 2). The modes vary in the brightness distribution pattern around the ring, which is a consequence of the sparsity of observing stations and the intrinsic variability of Sgr A*.[6] The averaged image in the top panel retains the features most commonly seen in the different clusters, while suppressing those features that appear infrequently.



*Source: Reproduced from Figure 3 of EHT Collaboration et al.[4]*

**Figure 2:** Image of the supermassive black hole Sagittarius A* located at the centre of our galaxy. The main image (top) was produced by averaging together thousands of images created using different computational methods — all of which accurately fit the EHT data. The images are clustered into four groups based on similarity of features (bottom). The bar graphs show the relative number of images belonging to each cluster, with their heights indicating the relative contribution of each cluster to the main image.

## Astrophysical implications

The EHT Collaboration developed a large library of simulations representing 200 general relativistic magneto-hydrodynamical models of black hole physics. These fiducial models vary in the strength and structure of the magnetic fields surrounding the black hole, brightness of the outflow region, the inclination angle with respect to the line of sight, and the black hole spin.[9]

All fiducial models were tested against 11 constraints derived from the 230 GHz EHT observations, as well as prior observations of Sgr A* at lower radio frequencies (86 GHz), infrared, and X-ray wavelengths. None of the models passes all 11 constraints, displaying greater variability than warranted by the data in combination with the other constraints. Excluding the strict constraint on variability, the data prefer models of a 'face-on' (rather than highly inclined) shadow, with a prograde spin (with the disk-like accretion flow swirling in the same direction as the black hole spin), reasonably efficient jet outflow (motivating future studies), and ordered magnetic fields that impact the dynamics of the accretion flow.

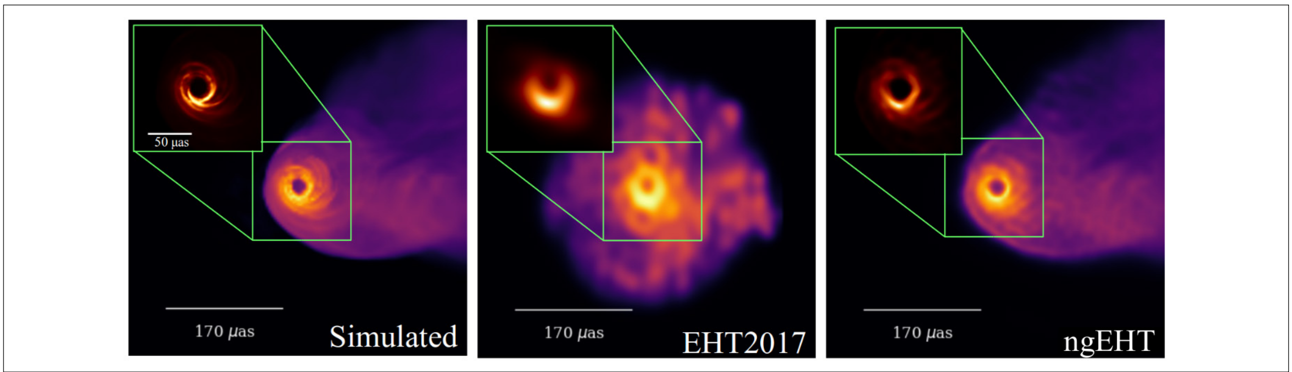
To compare with theories of gravity, we have to convert the measured morphological properties of the images to a common physical scale so that various physical properties of the black hole may be estimated.[10] This is accomplished by calibrating the measured ring diameter $d_{ring}$ to a quantity called the angular gravitational radius $\theta_g$, which is directly related to the size of the event horizon. A suite of 100 data sets generated from general relativistic magneto-hydrodynamical simulations with known $\theta_g$ values was used to perform this calibration. Applying the outcome of this process to the measured ring diameters for Sgr A* yields a $\theta_g$ value consistent with theoretical predictions and an estimated mass of $4^{+1.1}_{-0.6}$ million times the mass of the Sun.

The above measurements are consistent with what is expected for a Kerr black hole, defined as a black hole that is fully described by its mass and spin. As all astrophysical black holes are expected to be Kerr black holes, quantifying the potential deviations from the Kerr metric is necessary to understand how gravity operates in the vicinity of black holes. Using a calibration data suite consisting of 145 synthetic data sets, generated from both Kerr and non-Kerr models, the EHT Collaboration calibrated the expected shadow sizes against the measured ring diameters for Sgr A* and estimated the deviation from the Kerr metric to be within 10%.[11] Together with the deviation metric derived for M87*[12] and for two gravitational-wave events detected by LIGO/Virgo for stellar-mass binary black holes[13], we find that the same black hole metric is consistent over eight orders of black hole mass, as predicted by general relativity, proving Einstein correct yet again.

## Africa's potential role in future black hole imaging

Three new stations have been added to the global EHT network since the 2017 observing campaign, with the goal of expanding this array by a further six to ten additional stations spread across the earth towards the end of this decade. This expanded array is referred to as the next-generation EHT (ngEHT).[14] Each additional station in the ngEHT contributes an increasingly larger number of new measurements. The locations of these new sites determine how the gaps in the virtual earth-sized telescope are filled. Therefore, carefully positioning them around the world, minimising any large gaps such as those found in Africa, can significantly improve the quality of the images (Figure 3). Improved images contribute directly to improved tests of general relativity and to new insights on the role of magnetic fields in the jet launch and accretion process. Promising studies have also been made to complement the ngEHT with space-based stations, but that is likely decades into the future.[16,17]

Establishing observatories around the planet must also take practical constraints and costs into consideration, including road and power




*Source: Reproduced from Figure 4 of Blackburn et al.[14]*

**Figure 3:** Snapshot of a general relativistic magneto-hydrodynamical simulation of M87[15] (left). Image reconstructed using the 2017 EHT array (middle). Image reconstructed using the proposed ngEHT array at both 230 and 345 GHz (right) recovering both the ring and the jet with far superior contrast and fidelity.

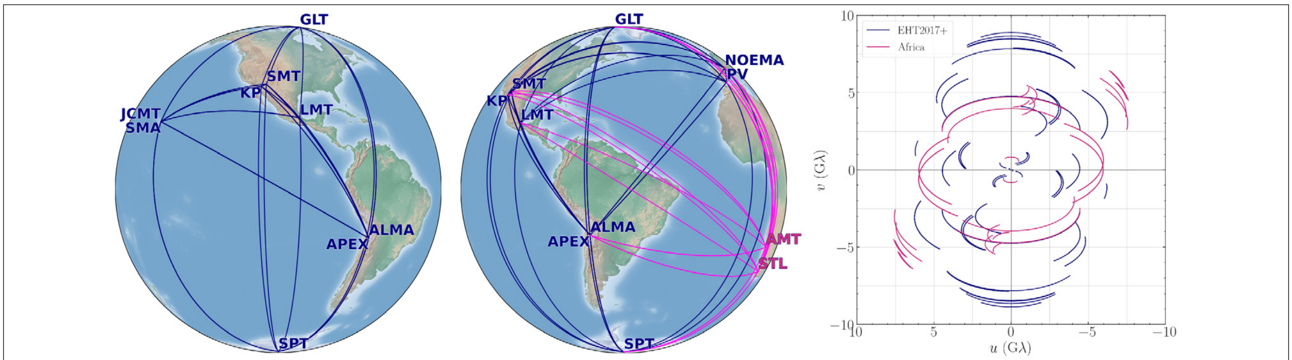



**Figure 4:** Locations of existing (EHT2017+, blue) and proposed (pink) EHT stations in Africa (left, middle). Baseline coverage of Sgr A* observation during one night in April (right). The (*u*, *v*) coordinates represent projected baseline vectors for each pair of antennas in units of the observing wavelength. As the earth rotates, an individual baseline will trace out an arc. The blue arcs correspond to the baselines formed by EHT2017+ and the pink arcs correspond to the baselines contributed by the African stations.

availability. South Africa has well-established infrastructure protected by legislation at its astronomical sites and boasts world-class astro-engineers at the forefront of their craft (an example being the EHT's use of the ROACH2 boards). Moreover, as with palaeoanthropology, there are contributions to astronomy that can only be made from southern African soil, especially in the case of the ngEHT. The Galactic Centre lies in the southern sky, passing directly above us here in southern Africa, which is optimal for astronomical observations. New technology such as a cutting-edge simultaneous multi-frequency receiver design and the phase-transfer technique[18] enables EHT stations to be located at relatively low-altitude sites (1500–2500 m) where atmospheric conditions are not as pristine as at the South Pole or above 5000 m in the Chilean Andes. This means well-established astronomical sites in the country can be used, decreasing project costs by a substantial factor.

Figure 4 shows the number of new baselines added to the existing EHT array by the introduction of two potential stations in Africa: (1) the Africa Millimetre Telescope (AMT)[19] located at Gamsberg in Namibia, and (2) a millimetre-wave telescope located at Sutherland (STL) in South Africa, as an example site that holds this strategic geographic advantage alongside established infrastructure. The baselines formed by AMT and STL with existing EHT stations contribute to improved angular resolution along different directions for both major EHT targets – M87* and Sgr A*. Figure 4 demonstrates this by plotting the *uv*-coverage (a plot showing where the gaps in the virtual telescope are filled) of this enhanced array during an example Sgr A* observation. Crucial new baselines of different lengths at different orientations are introduced by the African stations, enabling enhanced angular resolution and contrast ratio of the resultant images. Potentially just as important are the unique, approximately north-south oriented short baselines (~1000 km) added to the array by the intra-African baselines between Namibia and South Africa. This currently missing information could be important in connecting black hole shadows to larger-scale features such as jets. Moreover, by better constraining the large-scale emission with these short baselines, we improve the optimisation and performance of the imaging algorithms to produce the shadow images. Clearly, Africa offers this new black hole imaging enterprise distinct and unique value towards fundamental tests of gravity and understanding how relativistic jets are launched from black holes.

However, deeper, more equitable involvement by African countries and researchers in large-scale international scientific collaborations has the potential to make societal contributions of a broader nature. As has been demonstrated with the MeerKAT telescope, the precursor to the Square Kilometre Array, the impact of innovative mega-projects on human capacity and technology development is profound.[20] Perhaps a deeper legacy of African EHT stations would be to spur further innovation, inspire local youths to excellence, and foster greater equality in science collaboration between the Global South and the rest of the world.

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# Electrification of minibus taxis in the shadow of load shedding and energy scarcity


**Significance:**

Electrification is expected to decarbonise transportation and forms part of the agenda to delay climate change. Electric vehicle sales have ballooned and production of combustion engines will stop soon. In sub-Saharan Africa the transition is slow. Minibus taxis carry more than 70% of commuters and little is known about their electrification requirements. Electrical demand planning is better with vehicle-based data than with passenger-based data. Stationary times provide ample time for taxis to recharge from the grid and solar, but the latter requires substantial stationary battery capacity to negate grid-impacting fast charging. Taxi energy requirements are approximately 200 kWh/day on average.


Electric vehicles are heralded as a silver bullet to globally decarbonise the fuel-guzzling transport sector. The Intergovernmental Panel on Climate Change (IPCC) estimated in 2014 that the transport sector generated 23% of the global energy-related greenhouse emissions.[1] The development of low-carbon transport in cities is part of the global agenda to delay climate change[2] and relates to three of the United Nation's Sustainable Development Goals[3]. Meanwhile, electric vehicle sales have increased substantially in the Global North and many global vehicle manufacturers plan to stop production of combustion engines as early as 2030.

However, in sub-Saharan Africa, the transition to electric vehicles continues to be painstakingly slow. Privately owned minibus taxis (MBT), the mainstay of transport in the region, are ubiquitous in the developing cities and rural areas of sub-Saharan Africa. They cater for 83% of the so-called 'paratransit' industry, which carries more than 70% of daily commuters in sub-Saharan Africa. This informal sector is now faced with the need to transform to an electrical energy source.[4-8] Currently, very little is known about the energy requirements of MBT, especially given their unique and mostly unknown mobility patterns.[9]

This uncertainty on the vehicle side of this revolution is further overshadowed by the looming threat of energy scarcity on the electricity supply side. Fragile grids in the region are struggling to keep the lights on, even with existing demand before electrification of vehicles, and therefore pose a substantial stumbling block to the mobility of electric vehicles.[10]

In a recent seminal publication on the topic, Collett and Hirmer[9] evaluated the readiness of paratransit in sub-Saharan Africa to transition to electric vehicles. They highlight the potential benefits of the shift, but identify the lack of data as the main impediment to making the transition a reality.[9]

Crucial knowledge gaps include the potential demand and where and when this demand will occur. We explore these questions provide some answers from our recent research.[11-14] We also highlight specific areas of remaining challenges and future research.

## Background

Paratransit in Africa's developing countries differs substantially from that in developed countries. It operates somewhere between private passenger transport and conventional public transport in terms of cost, scheduling, routes and quality of service, and covers both urban and intercity travel.[15] This collective mode consists of shared-ride, demand-responsive privately owned vehicles such as the minibus taxis of Johannesburg, Lagos, Kampala and Nairobi or Kampala's motorcycle taxis ('boda bodas') and Nairobi's tricycle taxis ('tuk-tuks').[15-17] Unfortunately, they are notorious for poor safety and inefficiency.

Given its entrenched position in society, its economic gravity, and the political power of the multitude of taxi associations, MBTs are unlikely to be phased out anytime soon. However, the environmental cost of running them is worrying. It has triggered discussions about the possibilities of transitioning to electric minibus taxis (eMBTs) as part of the global electrification and sustainability agenda.[9,18]

In South Africa, between 250 000 and 300 000 MTB are spread across approximately 20 000 owners. Electric vehicle models indicate a power efficiency of approximately 1 kWh/km. Initial evaluations of current patterns have shown distances of approximately 200 km/day.[12] Electrifying the taxi industry will therefore add considerable strain to the grid, which raises the question: is our grid ready for this additional energy requirement? And do we have sufficient data to answer this question adequately?

The current grid in South Africa, run by parastatal behemoth Eskom, has an installed capacity of 48 GW, which reduces to 24 GW during regular breakdowns and maintenance programmes. With rolling regional blackouts (colloquially known as 'loadshedding') being a regular occurrence, instability and the lack of electrical supply present roadblocks on the highway to a future eMBT fleet. Eskom comprises 83% coal-based electricity generation. Thus, some researchers argue that deploying electric vehicles shifts gasoline usage and urban emissions to coal-fired power generation and rural emissions, in some cases exacerbating GHG emissions.[10,19] This is solvable by introducing smart charging strategies and renewable energy sources, especially in the region's sunny climate.[10,20,21] An accurate prediction of an eMBT fleet data set is thus of utmost importance to evaluate the impact of the transition.

Important stakeholders in this transition include those in charge of the vehicles, charging infrastructure, grid operators and electricity retailers, taxi owners and associations, and a plethora of governmental agencies. This complex web of agents needs to be convinced, not only of the importance of environmental sustainability, but also of financial viability.

## Reliable and adequate data

In a recent publication, we assessed the energy requirements of the paratransit system from the perspectives of two mobility data collection methods: using handheld mobile devices, and using GPS devices fixed in the taxis.[11]

### *Passenger-based data*

The first method, using the handheld mobile devices (often mobile phones) is commonly used by transport engineers in resource-constrained environments. This method involves fieldworkers boarding the minibus taxis as passengers and tracing the routes for the duration of the trip. An example of a compilation of such data we assessed is the 'Digital Matatu' data set, which was collected with mobile phones in Kampala, Uganda, and Nairobi, Kenya, and stored in the GTFS (general transit feed specification) format.[22,23]

### *Vehicle-based data*

The second method, which is more invasive initially and has a higher set-up cost, uses vehicle-mounted GPS trackers. The trackers continuously log and transmit their location and velocity to remote data-collection centres through the communications network (usually cellular). Our data set consists of data from over a year of GPS vehicle tracking in Kampala, Uganda and in Stellenbosch, South Africa. These data are then made available from a cloud server either as timestamped GPS traces, or as processed timestamped trip information that captures the origin and destination.

## Perspectives on energy and power results

### *Passenger-based data*

The passenger-based energy results are shown in Figure 1. Figure 1a shows the aggregated results for Kampala, in which all the individual routes in the data set and their related frequencies were aggregated to estimate energy requirements for the paratransit system (minibus taxis only). The figure shows the power requirements throughout the day and the aggregated energy demand as the day progresses. Importantly, this includes only the routes covered in the data set, and no extrapolation was done to include other routes.

Figure 1b shows the aggregated results for Nairobi, again with all the routes and their corresponding frequencies aggregated for a system-level energy representation. The aggregated power profile is substantially lower than that of Kampala, which peaks at 280 MW, while Nairobi peaks at a mere 90 MW. This may be partly because Nairobi has fewer minibus taxis than Kampala. However, a simple proportional calculation shows that the difference may also be partly because of under-representation in the passenger-based acquisition of routes. It is a drawback of this method of data capture that we have no way of knowing the taxis' destinations unless they had passengers collecting data.

### *Vehicle-based data*

The output of the eMBT simulation is shown in Figure 2 for Kampala and Stellenbosch. A clear typical temporal profile is apparent for the minibus taxis in both cities, closely matching the expected peak traffic hours. This profile indicates the energy requirements of the eMBTs, and already hints at some charging potential during the evening – probably from grid power – and some during the middle of the day – preferably from solar and wind power. It should be noted that the availability of these renewable sources are season, region, and weather dependent.

The mean instantaneous power demand profile of a working weekday in Kampala is shown in Figure 2a. 'Power demand' refers to the net power drawn from the vehicle's battery. The mean energy required per day was 220 kWh, and the mean distance was 224 km (obtained by integrating the power and speed profiles, respectively).

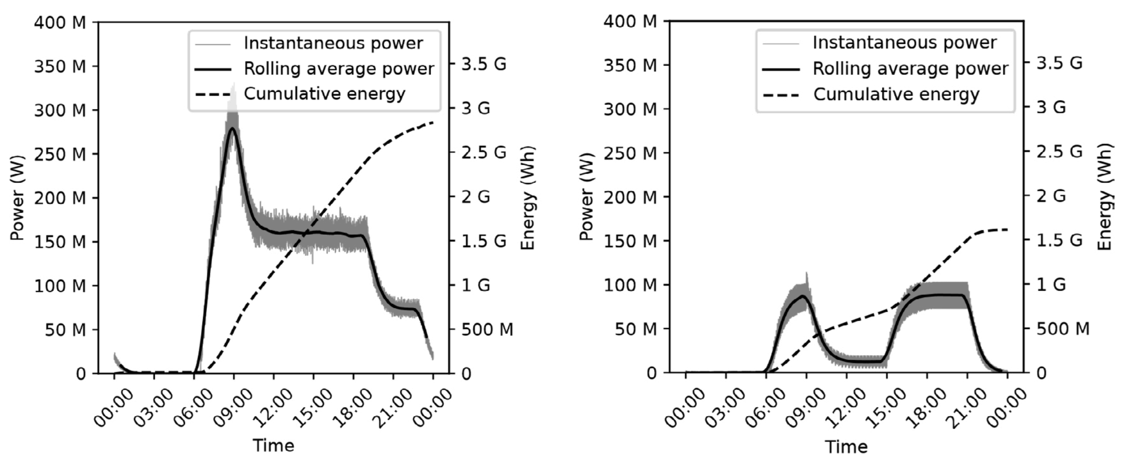
The mean instantaneous power demand for a working weekday in Stellenbosch is shown in Figure 2b. Not only is the profile clearly defined, but the variation between taxis, shown by the minimum and maximum profiles in the shaded area, is minimal. The only substantial deviation is the increase in the maximum profile just after 21:00. This is because some taxis start long-distance weekend trips on Friday evenings.[24] The mean energy required per day was 212 kWh, and the mean distance was 228 km.

The distribution of energy usage per day is shown in Figure 3a for each of the eight taxis in Kampala. Their energy usage is similar, with the median energy per taxi per day across all taxis ranging from 108 kWh to 335 kWh, with the mean of the medians equal to 220 kWh. The taxis travelled a mean distance of 224 km, leading to an energy efficiency of 0.98 kWh/km. The distribution of energy usage per taxi per day is shown in Figure 3b for the nine taxis in Stellenbosch. The taxis' energy usage is similar, with the median energy per day per taxi ranging from 189 kWh to 252 kWh, with the mean of the medians equal to 215 kWh.

The results show that a maximum usable battery capacity of approximately 500 kWh would be sufficient for urban travel, if charging is limited to the stationary period before the day's first trip, and, for 75% of the time, a 303-kWh battery would be sufficient. This indicates that the demand is much greater than the battery capacity of currently available passenger electric vehicles. To reduce the battery size and capital costs of the vehicle, it would be necessary for eMBTs to charge at various stops during the day, which could lead to a loss of potential revenue for the drivers.

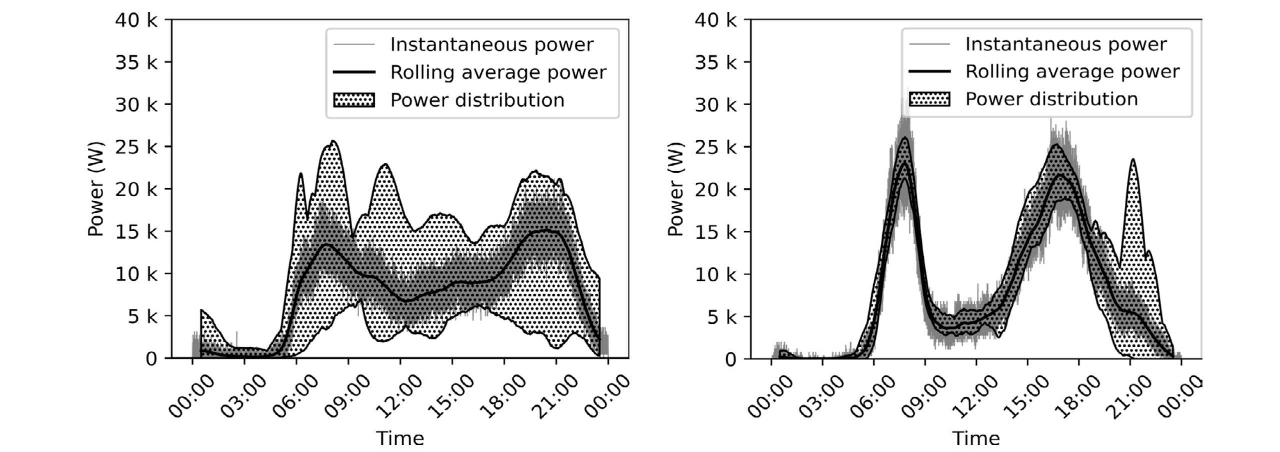
### *Passenger versus vehicle data*

The Kampala profile from vehicle tracking in Figure 2 is substantially different from the passenger-based profile captured in Figure 1.



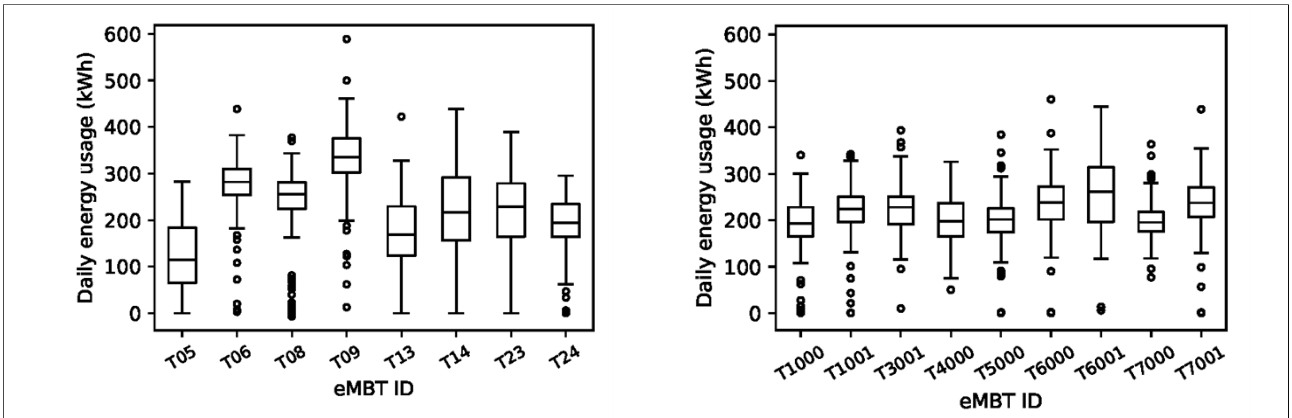

(a) Kampala (b) Nairobi

**Figure 1:** Daily power and energy profiles of minibus paratransit systems in Kampala and Nairobi, from passenger-based data.




(a) Kampala (b) Stellenbosch

**Figure 2:** Summary of electrical demand for all the simulated electric minibus taxis' daily power (instantaneous and rolling average) sampled per second, expressed per taxi.




(a) Kampala (b) Stellenbosch

**Figure 3:** Daily energy usage for each simulated electric minibus taxis (eMBT).

To illustrate the difference between the two data source methods, in Figure 4 we show Kampala's energy profile from the two vantage points. The overlay shows the passenger-based energy profile, which was down-scaled by the number of taxis in Kampala (25 000 according to Spooner et al.[25]), and our vehicle-based energy profile.

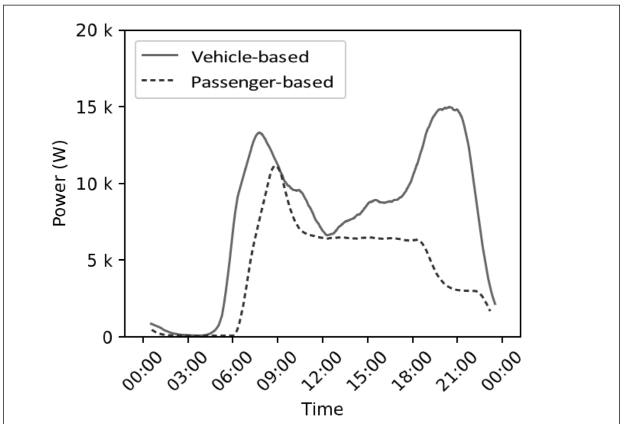



**Figure 4:** Comparison of Kampala per-vehicle power profiles derived from passenger-based and vehicle-based data.

The differences are stark. First, it is clear that the taxis started moving between 4:00 and 5:00, before the fieldworkers managed to get on board. Second, the passenger-based profile grinds to a halt just before supper time. But we know that the minibus taxis in our samples happily chug away until after 21:00.

Thus, although passenger-based data are readily available and often used, their usefulness in energy analyses is limited for several reasons:

- The data do not adequately reflect the mobility patterns from a vehicle perspective. They give information on a particular route's energy requirements, which is less useful.
- Fieldworkers will only track the MBT for a limited number of hours in a day, mostly according to normal office hours.
- Passenger waiting time, rather than vehicle waiting time, is captured with this method.

The vehicle-based method is much more useful for energy analysis than the first method, as it adequately and reliably captures the vehicle's moving and stopping patterns, which are very useful for energy analysis. Relying on the data captured by fieldworkers would therefore lead to a substantial error in energy estimations, exemplifying the crucial need for vehicle-based data collection. This adds weight to the statement by Collett and Hirmer[9] that stresses the need for adequate and reliable data.

### *Charging opportunities*

To discover the eMBTs' opportunities and requirements if they are to charge during stationary periods, we did a 24-h analysis of the start times and the durations of stop events. The analysis shows what the average charger capacity should be if a vehicle is charged using only power from the local electrical grid. We applied a minimum stop duration of 20 min to ensure that only stops that are valid for charging would be identified and that drop or pick-up-and-go events were not included as charging opportunities.

Figure 5 shows the distribution across days of stop events with the minimum 20-min stop duration threshold applied. The Kampala scenario shows that each taxi's daily stop durations vary considerably. However, for both scenarios, the median stop duration does not vary much across taxis. The median duration per day ranges from 10 h to a maximum of 18 h for Kampala; that for Stellenbosch ranges from 15 h to 18 h.

To calculate the charger capacity, we used a relatively high energy demand and a relatively short charging time for an average demand situation. We used the average of the 75th percentile of the energy usage from Figure 3, and the average of the 25th percentile of the 24-h stop duration times from Figure 5. For Kampala, these were 273 kWh and 11.5 h, respectively, and resulted in a charger capacity of 24 kW. This calculation assumes a constant charging profile for the sake of simplicity, as a real electric vehicle charging profile would require additional modelling. With these assumptions, 23.7 kW for 11.5 h would fully recharge a taxi on most days. For Stellenbosch, these figures were 247 kWh and 15 h, respectively, resulting in a charger capacity of 16.5 kW.

### *Grid versus solar photovoltaic charging*

We set up the System Advisor Model (SAM)-based photovoltaic (PV) model to calculate the energy available from PV sources and to study the daily charging potential for each eMBT in a synthetic fleet of nine eMBTs in Stellenbosch. Stop events were analysed to further assess the battery charging potential from solar PV by evaluating the times and duration thereof. These 'daily PV charging potentials' were aggregated for each taxi and plotted as box plots.

The complete inactivity observed between midnight and 5:00 for Kampala and between 23:00 and 5:00 for Stellenbosch indicates the best opportunity to charge from the grid. As this is a considerable amount of continuous time, charging can take place at low power to prolong battery life. But where are the taxis located during this time? The answer to this question could introduce new obstacles to the charging infrastructure.

Inactivity during the middle of the day provides the opportunity to charge from solar PV to reduce the load on the electrical grid and to reduce the size of the installed battery in the eMBT. The variation of charging potential between taxis is low, indicating that the taxis follow similar patterns during the daylight hours, and that they would require similar charging infrastructure.

After evaluating the needs of eMBT in Stellenbosch, approximately 320 $m^2$ of solar installation would be required per taxi to ensure its daily needs are met at least 50% of the time if no storage is used. Given the estimated 285 000 taxis in South Africa, our analysis indicates that to charge all the minibus taxis from the national grid will require 9.72% (61.27 GWh) of the current daily national installed (rather than operational) generation capacity. Reducing this strain with the use of solar PV is pivotal in the transition to eMBT.

## Conclusion

The threat of climate change has propelled an energy revolution from vehicles with an internal combustion engine to electric vehicles in the Global North. Influenced by market forces and supplier preferences beyond its borders, this wave will eventually sweep across the Global South's organically evolved and notoriously chaotic paratransit systems and fragile electrical grids. In addition to the scarcity of electricity, the lack of data on the mobility of MBT poses a substantial challenge to these efforts.

We considered how the dissimilar mobility characteristics of minibus taxis will translate into electrical requirements. Also, because these vehicles park spontaneously at tacitly known stops of the drivers' choosing, for durations determined by passenger demand, the charging potential at these stops has hitherto been unknown.

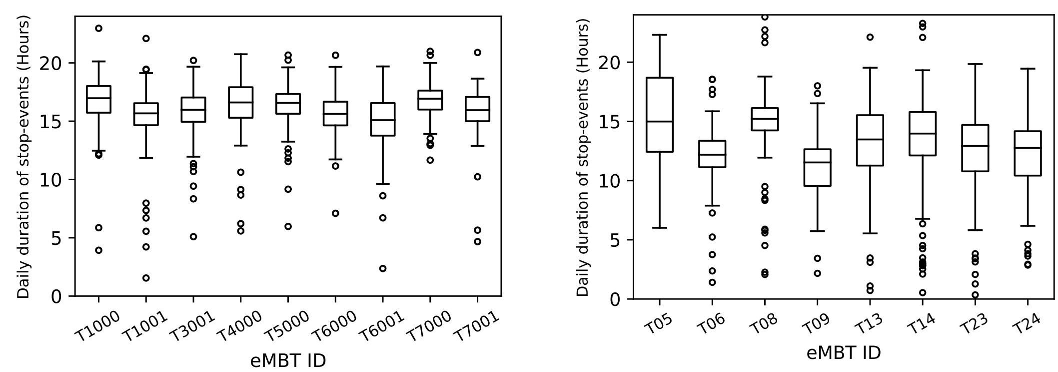
We found that passenger-based data may be useful for determining the aggregate energy load of a whole city or a single route. However, these results could be wholly incorrect if the passenger-based tracking is not reliable. On the contrary, vehicle-based tracking provides a reliable means of determining the energy requirements of a vehicle, and with sufficient adoption it could be used to determine system demand too.

Our results show that the electricity demand of the taxis was similar, with a nominal 250 kWh required per median day if no additional charging capacity is provided. This demand increased to 420 kWh when we included all days, except for one taxi, which required 490 kWh. The median stops per day ranged from 15 h to 18 h, suggesting considerable potential for charging.

Although these results are location specific, the models can easily be modified to suit the context of other developing countries.

The taxis with the shorter stopping periods, and hence the lower potential for charging, will need more energy because they are more mobile. Nevertheless, a nominal 24-kW charger will suffice when only charging only from the grid – if the grid is fully operational, which should not be taken for granted.

Given the constricted electricity production, the sustainability of future paratransit needs to be coupled with a transition to renewable energy. However, renewable sources are intermittent, and the output is not necessarily matched, in the time domain, to the load. It must therefore be matched by substantial investment in battery storage to decouple demand and supply temporally. This could take the form of stationary battery storage at charging stations or batteries used in swapping schemes. Stationary battery storage can be used to charge slowly from the grid or renewable sources when available – reducing the grid load – and can then be used to discharge faster into vehicles without burdening the grid. Batteries used for swapping can also charge slower from the grid or renewable sources when available – with a concomitant reduction on grid power load – and will probably be faster to swap than charging a vehicle with a fixed battery.




(a) Kampala
(b) Stellenbosch

**Figure 5:** Daily durations of minibus taxi stop events with a minimum duration threshold of 20 minutes.

## Future work

Many challenges and unknowns remain in the transition to an electrified minibus taxi fleet. These can be classified as either on the vehicle's demand side or on the electrical supply side.

We have answered the question of the vehicle's energy requirements by simulation. However, these simulations were limited to an urban environment. But current internal combustion energy vehicles seamlessly transition to long-distance trips, which impose hitherto undetermined energy requirements for the vehicle. Moreover, the mobility analysis was performed with actual route way points, but with a micro-traffic simulation model that estimates energy efficiency – approximately 0.95 kWh/km – and which still needs to be validated with data from actual taxis in the region, captured at high temporal resolution (e.g. accelerometer or GPS).

On the supply side, many unknowns remain. These unknowns include the impact on mobility of the burden of loadshedding and the impact of electrifying on the low-voltage and medium-voltage distribution networks.

Fortunately, opportunities also lurk in the shadows. One such opportunity is the potential use of second-life vehicle batteries from developed countries in renewable powered charging stations. Another is the assessment of battery swapping schemes in the minibus taxi context, for both urban and long-distance travel to reduce stopping times.

## Competing interests

We have no competing interests to declare.

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# The value of arboreta in South Africa

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**Significance:**

- Arboreta are documented, living collections of ligneous species cultivated for research, education and display.
- Arboreta are a valuable resource for the forestry industry as gene banks.
- Arboreta, together with botanic gardens, form a useful network of sentinel sites for plant pathogens and invasive species.
- A survey of the species composition and status of arboreta in South Africa would be an important contribution to our botanical knowledge.

Since antiquity, collections of living trees, or arboreta, have been established for diverse religious and aesthetic purposes.[1] Naturalists became increasingly aware of their scientific value as early as the 16th century[2], in particular as a living resource with which to study taxonomic questions that arose with the influx of species into Europe from botanical exploration[3]. The economic and scientific importance of introduced tree species was realised by many of the major landowners in the United Kingdom and from 1750 and 1850 many arboreta were established on private estates and in botanic gardens.[4] During the 19th century, arboreta were increasingly used as acclimatisation trials for introduced tree species in Europe[1,5,6], America[7], Australia[8] and South Africa[9]. The first arboreta to be established in South Africa were Arderne Gardens in 1845[10] followed by the Durban Botanic Gardens in 1851[11]. Acclimatisation studies developed into a new research field during the 19th century and the term 'acclimatisation garden' became widely used by professional and amateur botanists.[12]

## Defining an arboretum

Definitions of an arboretum vary from vague, such as a botanical tree garden[13], to specific, for example, a comprehensive collection of arboreal species, varieties and forms, of both alien and indigenous species, that can be cultivated in one locality[14]. In some cases, such as the Morton Arboretum[15], University of Wisconsin Arboretum[16], the Holden Arboretum[17], the Dawes Arboretum[18] and Connecticut Arboretum[19], the term is used as a synonym for a commons – a relatively large legally protected area (in the aforementioned cases 485, 1255, 728 and 182 hectares, respectively) that includes prairies, natural woodland, wetlands and landscaped areas, with some sections receiving little, if any, management. The optimum size of an arboretum is largely determined by its purpose, whether it is to address particular research questions or is intended for education and display.[1] Baas-Becking[1] differentiated between a forestry and dendrological arboretum, recommending a minimum of 50 hectares for the latter which would have wider research applications than strictly silviculture. This is a recommendation that will undoubtedly vary with the amount of land available. Hartley[20] observed that the renowned 19th-century Scottish botanist J.C. Loudon considered the ideal size of an arboretum that which allows sufficient space for each species to attain its full size and character.

Although he never defined an arboretum in his *Arboretum et Fruticetum Britannicum*, J.C. Loudon's concept of an arboretum is similar to that of a botanical garden except that it is specifically aimed at ligneous plants, displayed following a natural system.[20] In South Africa, the term arboretum is associated with the systematic cultivation of trees and shrubs for display and research purposes.[21] While there is some overlap between the definition of an arboretum and a botanical garden (Supplementary table 1), we support a narrow arboretum definition as a documented or labelled collection of living, ligneous taxa, non-native or indigenous, cultivated for scientific research, educational and display purposes.

## Arboreta in forestry

One of the most important stages in forestry plantation establishment is selecting appropriate species for a particular region or site conditions[22] and arboretum experiments are the most practical way to facilitate this[23]. The fact that different species or provenances require particular climatic and edaphic conditions to perform favourably, is known as the Genotype x Environment interaction.[24] Thus it is important that species are tested in the setting for which they are intended.[25] In this way, new genotypes could be selected for particular applications and new sites, either for commercial timber industry[26] or for reforestation of degraded land[27]. Arboreta have been instrumental in selection studies for commercial timber species in South Africa and Tokai arboretum was the first to be established for this purpose (Supplementary table 2). Research into the performance and commercial suitability of kauri pines (*Agathis* species) was also done at Port Durnford arboretum (established in 1923), in KwaZulu-Natal, South Africa.[28] Whereas species selection trials are often a mixture of species, plant breeding programmes and provenance trials are often a series of ongoing trials[25] of a single species or cultivar where the goal is to select superior genotypes[29].

## Arboreta in horticulture

Urban forests are valuable as amenity plantings and for improving the aesthetic value of municipal areas.[30] Urban plantings are increasingly used as a resource in detecting new plant pests and pathogens and investigating the potential effects of climate change.[31] However, the selection of street trees is often based on what will grow at a site, the preferences of local people, and the availability of nursery stock.[32] Arboreta are labelled, catalogued collections with information on their establishment date and often the origin of the species they contain, giving them greater value over and above the substantial plantings of trees in urban settings because tree selection is more often driven by research questions. Arboretum trials are useful in assessing species for various urban and industrial settings.[33] Selecting trees with the appropriate size and shape decreases the maintenance costs of both the trees as well as the surrounding infrastructure.[34] To streamline the process of introducing new cultivars to horticulture in the USA, a National Arboretum introduction programme was started in 1971 to evaluate the performance of new cultivars.[35] The National Arboretum co-ordinates this evaluation programme but the growth and monitoring of plants is done at botanic gardens, arboreta, universities and nurseries that have signed a memorandum of understanding to be a co-operator in the programme, thereby converting established botanic gardens and arboreta into a network of test sites to determine the hardiness range of new cultivars.[35] Starting with Tokai arboretum, the Department of Forestry established a number of arboreta across South Africa which provided valuable information on the performance of tree species in the various climates. This information enabled the Department of Forestry to recommend tree species to farmers, municipalities and the public for amenity planting or particular applications such as windbreaks or soil stabilisation.[36]

## Arboreta as sentinel sites

The International Plant Sentinel Network functions as an early warning system through sharing information about new outbreaks of pests on alien collections in botanic gardens and arboreta.[37] Surveying introduced tree species in such collections has proven useful in detecting new insect introductions, as well as undescribed insect species that use the trees as refugia.[38] The International Plant Sentinel Network was started in 2013 and currently has 71 participating arboreta and botanic gardens, of which 7 are in South Africa: (1) Pretoria National Botanical Garden, (2) Free State National Botanical Garden, (3) KwaZulu-Natal Botanical Garden, (4) Harold Porter Botanical Garden, (5) Walter Sisulu National Botanic Garden, (6) Kirstenbosch Botanical Garden and (7) Stellenbosch University Botanical Garden.[39] In 2016, a Sentinel Plant Project was started by the South African National Biodiversity Institute in conjunction with the Forestry and Agricultural Biotechnology Institute (FABI); since then 53 pests have been detected from South African arboreta and botanical gardens.[40] The polyphagous shot hole borer beetle, and it is associated fungal symbiont *Fusarium euwallaceae*, was detected from such a survey at the KwaZulu-Natal Botanical Garden in 2017.[41] The continued introduction of pests is likely to continue with continued trade and this is a significant threat to biodiversity across Africa.[42]

Because arboreta contain introduced species, they can also act as point sources for future plant invasions. With a change in climate, new horticultural species will be introduced, providing potentially new invasive species.[43] The sharp increase in the numbers of botanic gardens and arboreta since 1950 suggests that they still have the potential to represent a pathway of plant invasions.[44] In addition, the rate of new plant introductions has increased steadily since the 19th century and shows no sign of decreasing.[45] The evaluation and development of tools for detecting and monitoring new plant invasions was highlighted by Van Kleunen et al.[46] among the important points in managing future horticultural invasions. Arboreta within South Africa represent a valuable resource for this purpose.

## Arboreta in conservation

The role of arboreta and botanic gardens in botanical exploration continues; however, there is an increasing emphasis on their involvement in botanical research and the conservation of genetic resources.[47] Ex-situ conservation is the safeguarding of particular genotypes outside of their indigenous range and is useful when a threatened species has a very restricted indigenous range and arboreta and botanic gardens are currently the greatest contributors to ex-situ tree conservation.[48,49]

An important question to be considered is the conservation value of the arboreta as gene banks, in particular, those containing unique and red-listed species. Accurate species inventories are an important foundation. It is nevertheless necessary to determine the genetic diversity represented in a collection itself.[50] Adaptation to a new environment occurs along with sexual reproduction and this could cause a gradual change in the genotype being conserved ex situ from the genetic composition of the populations in the indigenous range.[51,52] Ideally, in-situ and ex-situ conservation should be combined for the conservation of a species to be most effective.[52] Through additional infrastructure, such as climate-controlled conservatories, arboreta can also expand their collections to include species that would otherwise not survive cultivation under the prevailing climate. The Princess of Wales Conservatory, at the Royal Botanic Gardens, Kew, houses many plant species from tropical regions such as the famous giant water lily *Victoria amazonica.*[53] In South Africa, Kirstenbosch Botanic Garden has successfully cultivated many bushveld plants from a subtropical climate (such as the baobab [*Adansonia digitata*]) in the Kirstenbosch Conservatory, despite being in a Fynbos biome with a Mediterranean climate.[54]

The ex-situ conservation and silvicultural research on threatened species is the goal of the non-profit Central American and Mexican Coniferous Resources Co-operative (Camcore) focusing on four genera: *Pinus, Eucalyptus, Gmelina* and *Tectona*.[55] This initiative was started in 1980 and currently includes 29 forestry companies from 11 countries as active members.[55] Conservation is an obligation of membership of Camcore and each company is responsible for the well-being and maintenance of those species under its care.[56] South Africa has been part of the Camcore initiative since 1983, with six conservation parks containing 12 *Pinus* and 1 *Eucalyptus* species.[57] The research questions and projects of which arboreta are becoming a part, seem to be of an increasingly national and international nature over time (Supplementary table 2). Where arboreta were mainly used in the early 20th century to select suitable commercial or amenity planting species, in the late 20th and early 21st centuries, they have been effectively used in biosecurity research globally as well as in climate change research, such as the REINFFORCE network[58] across Europe.

## Conclusion

Longstanding living collections of alien species have considerable research value for improving our understanding of pure and applied research problems.[59] The first assessment of South Africa's forestry arboreta was done by Poynton in 1957[60] followed by an unpublished survey by Poynton and Rycroft in 1986[21]. Arboreta represent an important resource for education, research, conservation and recreation and a survey of their current status would be an important step in using them for these purposes. Replacement cost theory is one way of placing a value on living plant collections. A complicating factor in this, is that living plant collections (as with herbarium collections) cannot be replaced, and the replacement value is more a measure of the investment made in establishing such collections.[61] Alien tree species are of prime importance to forestry industries in the tropics[62], and in the past there has been little in the way of procedures governing the movement of tropical tree germplasm between countries[63]. The Nagoya Protocol on Access and Benefit Sharing that was launched in 2014[64] creates barriers to the exchange of biological material; those countries with existing collections of alien plant material will be at an increasing advantage over time[65].

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## Competing interests

We have no competing interests to declare.

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# Some significant South African contributions to engineering

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**Significance:**

To mark the centenary of the University of the Witwatersrand (Wits), we review several major engineering achievements made over the last century by South African citizens, or individuals educated in South Africa – several of these contributions were made by Wits graduates and academic staff members. Equally significant are some outstanding contributions to engineering education. There is no sense in which this review is exhaustive but is more a reflection of the authors' personal interests and expertise.

The University of the Witwatersrand (Wits) celebrates its centenary in 2022. As part of this celebration, we recall some of the contributions made by South Africans to the most significant engineering achievements of the last century. Space limitations have forced us to limit our selection to a handful of these many brilliant contributions – many of which have an association with Wits. The selection we have made is inevitably coloured by our personal knowledge, our experience and interests, but also our ignorance. We offer no ordering or prioritisation as to whom we think might have contributed most. On topics such as this, one is unlikely to ever reach consensus.

This leads us to another issue: what is engineering, and who should be categorised as an engineer? In recent times, a lot of research and development work is undertaken by large teams, with members drawn from a multiplicity of different disciplines. Examples are the ITER nuclear reactor and the Large Hadron Collider whose missions are to investigate, respectively, the viability of fusion power generation and the frontiers of particle physics. Are these physics projects? The answer is surely 'yes'. Are these projects undertaken predominantly by physicists? The answer is 'no'. Both projects involve mathematicians, chemists, computer scientists, and engineers of many varieties.

To further muddy the waters, one might ask the question: what type of engineer is so and so? As engineering educators, we find a diversity of opinions on this subject too. At one end of the spectrum, one finds institutions that offer courses that are arguably over-specialised such as engineering acoustics. After completing such a course, we suppose that one becomes an acoustics engineer. Towards the other end of the spectrum, Cambridge and Oxford, for example, offer courses in engineering science which are broadly based and focus on the fundamentals of mathematics, physics and chemistry. One also finds courses such as global engineering design that could encapsulate almost anything. Our theory of the case is that categorising engineering into electrical engineering, mechanical engineering and so on has clear administrative benefits, but one should be wary of letting this categorisation produce siloed thinking. Engineering is a broad discipline with porous and poorly defined boundaries.

In discussing the South African engineers that we believe have made outstanding contributions, the reader will notice that some start out as engineers of one variety and then metamorphose into what one could categorise as mathematicians, physicists, computer scientists, medical doctors and so on. These developmental changes can occur in the opposite direction too, when mathematicians, physicists and chemists become engineers. We believe that this adaptability of thinking is to be lauded, and for that reason we believe that a broad-based education that focuses on the fundamentals is the correct way to foster the engineers of the future. While it is surely right to recognise and celebrate our past achievements, it is arguably even more important to think about the things that are likely to facilitate the production of future generations of outstanding engineers.

We have grouped our selected outstanding engineering contributors into seven topic areas. In each case we provide an introductory overview, with person-specific contributions provided in the supplementary material.

## Biomedical engineering

Reginald William James (1891–1964) was Professor of Physics at the University of Cape Town from 1937 to 1956. James was a Londoner who entered St John's College Cambridge in 1909 to study natural science. He recalls that his lectures on physical optics combined the best content with the worst of delivery.[1] This ambivalent experience did not appear to do any long-term damage to his development as a physicist. In the fullness of time, he made a world-wide reputation for himself in X-ray crystallography. He was a fine experimenter, neat, careful and thorough, and an excellent designer of apparatus. His book, *The Optical Diffraction of X-rays*, first published in 1948, has been reprinted four times, and is rightly regarded as a masterpiece. In 1937, James left a position at Manchester University to take up a professorship at the University of Cape Town. In 1955, he was recognised for his services to science and elected Fellow of the Royal Society. His professional career reached its culmination when he served as Vice-Chancellor of the University of Cape Town during the absence of T.B. Davie in 1953 and 1955, and after Davie's death, from 1956 to 1957.

James had another distinction of relevance – he had two Nobel laureates amongst his former students. Alan Cormack developed the theory that led to the invention of the CT (computerised tomography) scanner, which uses X-ray scanning to probe the human body. Using related techniques, Aaron Klug was able to determine the fine structure of viruses using electron microscopy. The personal contributions of A. M. Cormack and A. Klug are covered in more detail at ***Biomedical Engineering*** in the supplementary material.

## Civil engineering

Here we celebrate the achievements of two of South Africa's most famous civil engineers: Jack Zunz and John Burland. One operated above ground level, while the other worked beneath it. Zunz is connected with the design and construction of some of the world's most famous structures, while Burland is credited with saving them.

Structural engineering, which is part of civil engineering, is the study of the 'skeletal properties' of constructed structures. The work of structural engineers includes the stability, strength, and rigidity of structures such as high-rise buildings, roads and bridges. This work must be integrated with that of architects and building services engineers – structural engineers also play an important role in the supervision of large-scale construction work.

Geotechnical engineering is another branch of civil engineering, and concerns the engineering behaviour of foundation materials such as soil, rock and clay. Computer modelling plays a major role in both structural engineering and geotechnical engineering. These calculations can be used to assess the strength and compliance properties of large buildings and structures. Computer modelling can also be used to determine the stability of slopes and cliffs, and establish the load-bearing capacity, settlement and deformation characteristics of foundational materials. The personal contributions of G. J. Zunz and J. Burland can be found at ***Civil Engineering*** in the supplementary material.

## Engineering education

The provision of quality engineering education is a matter of prime importance in South Africa. One clear example, which nobody can realistically seek to replicate, was the training that R. W. James gave to Cormack and Klug. It is all about establishing a strong basis in the fundamentals, and revelling in the challenges of intellectual diversity.

Despite glowing examples such as this, it is regrettable that one still finds the viewpoint that teaching is where 'real academics' go to die. Good teaching must be valued, with fast-acting managerial feedback loops used to correct poor performance. In our experience, poor teaching is more to do with inadequate training than wilful negligence, or an unfortunate attitude.

It goes without saying that to teach well, one requires proficiency in the material one is teaching – this goes side-by-side with being active in research. Suffering, periodically, the slings and arrows of hostile reviews keeps one on one's toes. Most quality institutions put great emphasis on teaching mathematics, physics and chemistry to their undergraduate students. It is not uncommon to have formally trained mathematicians, chemists and physicists on the academic staff of engineering departments. They also encourage breadth – students from both Oxford and Cambridge graduate with an MA in engineering science, although the students have a large selection of subjects to choose from in their final year.

Displacement activities such as the appreciation of 18th-century French poetry in quality engineering courses is uncommon. While there is no harm in such interests, in our opinion they do not fit into an undergraduate engineering curriculum – there is just too much other material to cover. Another bugbear of ours are ratings tables that encourage universities to become 'popular' so that they can attract both students and government funding. This encourages the provision of lightweight courses that are directed more to entertainment than to learning. Establishing sound fundamentals is hard work, and staff and students alike should appreciate this. Great teachers are loved by their students. They teach, encourage and guide their students, but they do not indulge them.

We pay homage to two great intellects and outstanding teachers: Arthur Bleksley taught applied mathematics to physicists and engineers at Wits, while Seymour Papert was particularly interested in learning processes in young children. Their personal contributions appear at ***Engineering Education*** in the supplementary material.

## Feedback control and circuit theory

In many ways, circuit theory and feedback control came together with the development of the telephone. Prior to the invention by Lee De Forest in 1906 of the 'grid Audion', propagation losses limited the distances over which telegraphy was viable. The Audion was the first successful three-element (triode) vacuum tube, and the first device which could amplify electrical signals. These devices are inherently nonlinear. Therefore, every time a signal was amplified in an early telecommunications network, noise and distortion would be amplified too. A second invention was required to tackle this problem. On 2 August 1927, a young Bell Labs engineer named Harold Black invented the feedback amplifier in a 'flash of insight' while riding the Lackawanna Ferry across the Hudson River on his way to work. Black recalled, 'I felt an urge to write, but I had nothing to write on and so I picked up my morning paper, which contained both a date and a blank page'.

It turned out that Black's feedback amplifier had a tendency to 'sing', or become unstable. Ringing caused by gain increases was expected, but ringing due to gain reductions required explanation. Feedback instability occurs in mechanical engineering systems too – an early example being Watt's flyball governor. These systems were designed so that as the speed of the engine increased (perhaps due to a load reduction), the flyballs spread apart, and the throttle on the steam supply was closed. As manufacturing processes improved, and the damping and friction in these systems reduced, they tended to 'hunt' – another form of oscillatory instability. In 1932, a Swedish engineer by the name of Harry Nyquist, wrote his famous paper 'Regeneration theory'[2], which explains how both gain increases and gain reductions might cause feedback instability. His so-called 'Nyquist diagrams' allowed one to design good systems using bad components. Nyquist's paper on regeneration theory is an important component of the connective tissue that binds mathematics, feedback control, and circuit and communications theory together. Nyquist made other important contributions to signal processing and communications theory.

Three South African theorists have made important contributions to the development of optimisation, control and circuit theory, illustrating their close connections. They are O. Brune, D. Q. Mayne and D. H. Jacobson. Their personal contributions are described at ***Feedback Control and Circuit Theory*** in the supplementary material.

## Radar and communications technology

The Second Boer War was the first time that wireless communications had been deployed in a time of war. In years prior, the British military had some success with the development of early wireless communications systems, but under conditions very different to those found in the South African veld. At the time, Maxwell's equations were in place, but many facets of electromagnetic theory, antenna design, and circuit design were still poorly understood. There were no amplifying devices such as transistors or vacuum tubes, and any notion of 'selectivity' was laughable. The early 'Marconi' equipment probably operated in the low megahertz range depending on the length of the antennas used. Given that the first military testing of Marconi's equipment began in 1896, with the Boer war breaking out only three years later, it is remarkable that this early war time deployment achieved anything useful at all.[3] On the brighter side, the fields of applied electromagnetics and radio science were both evidently 'useful', and also wide open to the memorable contributions of another three great South African engineers – B. F. J. Schonland, G.R. Bozzoli and T. L. Wadley – whose personal contributions are described at ***Radar and Communications Technology*** in the supplementary material.

## Spatial estimation and geostatistics

Electrical engineers are familiar with the notion of a 'filter' as a circuit with frequency-selective properties. These filters might block high frequencies, or extract signal components in a certain frequency range.

Further developments came with the application of statistical ideas to signal processing. One might have a signal that is distorted and corrupted by noise, and one might be tasked with extracting by some means or other the undistorted signal from its distorted noisy version – this is another form of 'filtering'. One can talk about an 'optimal filter' as one that provides an output that is closest, in some sense, to the original undistorted signal. This type of filter is required to attenuate noise and transmission distortion in long-distance telephony. Solutions to this type of problem go back to the work of Kolmogorov and Weiner in the 1940s. Weiner extended these ideas to cover 'prediction' problems, whereby the future value of a quantity is predicted from its noisy present and past values. A well-known application of prediction theory was anti-aircraft gun aiming, whereby a Weiner 'predictor' was used to estimate the future position on an aircraft so that anti-aircraft guns could be fired in front of it.

In the 1960s, these ideas were extended to cover signals and noise that had time-varying statistical properties. This new theory was named Kalman filtering after its originator R. E. Kalman. Kalman filtering also brought the so-called state-space modality into the picture. Kalman filters also play a central role in the solution of optimal control problems where they are used to 'estimate' the internal state of a system given access to the system's input and noisy output measurements. Estimation is also a term used to describe 'parameter estimation'. Parameter estimation is used to obtain estimate parameter values given noisy input and output measurements. In each of these problems the independent variable is 'time'.

Our focus here is spatial (rather than temporal) estimation. Let us consider, as an example, a Christmas pudding with coins buried in it. Let us suppose that we had a playful sister who helped make the pudding and distribute the coins in it. It so happens that she is also a trained statistician who is prepared to provide us with a list of locations where coins are either buried or not buried. She also provides us with statistical information about the spatial distribution of the coins (*the variogram*).

Accepting the challenge, we set ourselves the task of estimating the locations of the undisclosed coins using the information provided. We may well have thought that some data points were more significant than others, and that some form of weighting scheme was required. Upon further contemplation, we may have thought that particular emphasis should be placed on data that happened to be near a particular investigation point; this is *data proximity*. We may have also thought that we should discount data points that are close to points that we had already considered – *data redundancy*. If we already know about one point in space, there is arguably little new information to be gained from additional data points in the immediate neighbourhood. A third thing we might want to think about is *spatial continuity*. Suppose there are lines in space, that pass through our test point, that are equally likely to contain a coin. From this brief discussion we get the idea that spatial estimation is about finding an optimal weighted average of given spatial data in order to estimate the probability of finding a coin at an arbitrary location in the pudding.

The spatial estimation problem is the field pioneered by the South African geologist and engineer D.G. Krige. He conducted this work primarily in the context of gold mining, with the Christmas pudding acting as a surrogate for the gold-rich Witwatersrand. Krige's contributions are described at ***Spatial Estimation and Geostatistics*** in the supplementary material.

## Vehicle dynamics

Vehicle dynamics is a multi-faceted topic involving predominantly mechanical and electrical engineering, but chemistry and materials science become important in fuel and tyre design. In modern cars there are multiple motor-driven sub-systems that fall under the catch-all umbrella title 'mechatronics'.

Erasmus Darwin, grandfather of Charles Darwin, was a physician, philosopher, slave-trade abolitionist, and poet. As a physician, he had to visit patients in nearby villages using a horse-drawn carriage as transport. At the time, vehicular steering was achieved by rotating the front-wheel beam-axle assembly about its centre. This meant that the front wheels had to be small (so they could fit under the carriage during steering) – while steering the carriage took on the geometry of a three-legged stool. The small front wheels also led to a rough and uncomfortable ride (the front wheels tended to fall into ruts and potholes in the road) – a problem not entirely unfamiliar 200 years later in present-day South Africa! This 'unfortunate' steering geometry also meant that the carriage tended to capsize under cornering.

Erasmus Darwin, although a medical man, set about re-designing the steering system for horse-drawn carriages. In his new design, the front-wheel radius could be increased by mounting the wheels on short steerable stub axles near the front corners of the vehicle. Provided the steering linkage was designed correctly, the front wheel would run tangent to the track centre line, thereby eliminating scuffing between the wheels and the road. This new design meant that the carriage was easier for the horses to pull, it was less likely to overturn, it provided a more comfortable ride, and there was significantly less 'tyre' wear. As vehicle speeds increase, handling and stability issues become important.[4]

In the 1970s, Dr Herbert Scheffel, inspired by Darwin's work, set about solving stability and tyre-wear related issues that were plaguing the narrow-gauge South African railways. His ground-breaking work led to what is now known as the 'Scheffel Bogie', which was introduced to the South African Railway fleet of ore-carrying wagons in 1975. Scheffel's breakthrough enabled speeds of 245 kph (152 mph) to be achieved on narrow Cape Gauge railway lines. A little later, another South African 'speed freak', by the name of Dr Rory Byrne, emerged to become one of the world's top Formula One race car designers. The contributions of both men are discussed in more detail at ***Vehicle Dynamics*** in the supplementary material.

## Acknowledgements

While writing a wide-ranging historical review such as this, one is constantly aware that: (1) there are likely to be differences of opinion as to 'balance' and who should be included, and (2) that there are numerous people 'out there' who know a lot more about specific topics than we do. In order to mitigate both of these concerns we have benefitted from the guidance of several colleagues.

## Competing interests

We have no competing interests to declare.

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# Medicinal plant cultivation for sustainable use and commercialisation of high-value crops

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Many traditional healing systems are based on natural biological resources, and there is a general shift in most parts of the world towards natural medicine, with direct implications on the demand and supply of medicinal plants. This review highlights the economic importance of medicinal plants, their contribution to healthcare systems, and potential opportunities for rural economic development through cultivation. A systematic literature review with specific search terms related to medicinal plants was used to collect scientific and non-scientific information from peer-reviewed literature and grey literature databases. The findings indicate that trade in medicinal plants is increasing, and although they are considered minor crops compared to major food crops, their value is among the highest in the list of traded plants globally. The trade also serves as a revenue source for many rural livelihoods, with women playing a significant role. Medicinal plants contribute to primary health care in many developing countries, and they are also an essential source of modern drug discovery. Cultivation of medicinal plants offers emerging rural farmers an opportunity to grow these plants as new and alternative crops, thus reducing unsustainable wild harvesting and competition with established commercial farmers who mostly focus on food crops. Furthermore, medicinal plant cultivation should be promoted as one of the options for local economic development and sustainability through job creation, the revival of the rural economy, and income generation for small businesses, such as the transport businesses, involved in the value chain. Land accessibility, financial resources, and direct market access for rural communities can elevate their contribution to the industry. Formalisation of the lower levels of the medicinal plant trade is also recommended.

**Significance:**

- Cultivation is a viable option for biodiversity conservation of medicinal plants and ensuring a good-quality supply of plant materials.
- Cultivation of medicinal plants – a source of natural products used in product development – can contribute to job creation, income generation, and rural economies in developing countries.
- This review underlines the importance of medicinal plants in product development, the contribution of the industry to economies of different countries, and the potential for cultivation.

## Introduction

Plant biodiversity fulfils various needs for daily human livelihoods, including health care.[1] The contribution of medicinal and aromatic plants to the agriculture output is relatively small compared to food crops. Still, their value in terms of volumes traded is among the highest in the list of traded plants. Thus they are amongst the high-value minor crops.[2] Notwithstanding the potential contribution to national agriculture through commercial cultivation, medicinal plants contribute to primary health care in many developing countries, and they are also an important source in modern drug discovery.[3] There is a general shift in many countries from acute disease incidences and management, towards chronic disease incidence, with implications on pharmaceutical demand and supply.[4] Many traditional healing systems are based on natural biological resources, particularly plants. For example, 20% of India's flora, 18.9% in China, 17.1% in Vietnam, 16.5% in Sri Lanka, 15.5% in Thailand[3], and 10% in South Africa[5] are used as medicinal plants. Guided by the indigenous use of many plant species, several plant-based health supplement products are produced and marketed globally with the resultant increasing demands on good-quality plant raw materials.

Developmental pressure, with related habitat destruction and unsustainable harvesting, result in biodiversity loss.[6] Cultivation of medicinal plants provides several opportunities, including preservation of indigenous knowledge, access to primary health care through traditional medicine, local economic development, and job creation.[7,8] The developments mentioned above can be achieved through micro-enterprise development by indigenous and rural communities.[9] However, the cultivation of medicinal plants can sometimes be unprofitable due to competition with freely accessible wild-harvested plant materials.[10] Commercial wild harvesters can cause significant damage to medicinal plant populations and the environment.[6] This could be attributed to the pressure to generate income, with less concern for conservation. Recent statistics on medicinal plant trade and consumption are scanty, with limited information as medicinal plant trade is mostly part of an informal economy.[7] This review highlights the global trade and use of medicinal plants, the effects of cultivation practices on bioactivity, and perspectives on cultivated medicinal plants.

## Methodology

A systematic literature review was used to collect scientific and non-scientific information related to the aim of the study. Search terms were created to extract sources from peer-reviewed literature on the Web of Science, Scopus, Science Direct, and grey literature databases such as Google. The search terms were "commercialization of medicinal plants", "trade in medicinal plants", "cultivation of medicinal plants", "use of medicinal plants", and "acceptance of cultivated medicinal plants". Scientific articles and non-scientific literature published between 1995 and 2021, at the time of submission of the manuscript, were considered. To minimise non-target articles, less relevant publications were excluded after scanning through their titles and abstracts. To develop a list of selected medicinal plants and compounds isolated from their different parts for medicinal use, medicinal plants that were already commercialised or had the potential to be commercialised, originating from Africa or naturalised through cultivation, were considered.

## The global trade in medicinal plants

The development of plant-based drugs has been listed as the next significant development in commercial biotechnologies as it would offer an opportunity to supply low-cost, quality pharmaceuticals to marginalised communities in developing countries.[4] The trade in medicinal plants occurs at three primary levels: national (within countries), regional (across borders on a continent), and international (the formal export trade).[11] At all levels, the value of medicinal plants is not only in financial income but also in health care, cultural identity, and livelihood security. The global trade in medicinal plants is dominated by a few countries, with three international trade centres: Germany, the USA, and Hong Kong.[12]

The formal trade in plant-based medicine has had an attractive return on investment over the past years. The global traditional medicine industry was estimated to be worth USD60 billion in 2006.[2] In 2014, the worldwide trade in plant-based medicine was worth USD940 billion.[4] This shows an increase in the global trade from the estimated USD30 billion in 2000.[13] Accurate estimates in the trade are difficult because medicinal plants are also used for other non-medicinal purposes, and also because the increased global interest in medicinal plants has led to an 'underground' trade which is mostly not recorded.[13] In general, the reports show an increase in investment in the trade by individual countries, despite differences in the figures reported. For example, compared to USD800 million in 1980[4] and USD1.6 billion in 1999[14], USD17 billion was spent in the USA on traditional medicine in 2000[15], which was a relative increase of 20-25%. The traditional Chinese medicine industry alone was estimated to be worth USD83 billion in 2012.[15] In India, the trade in herbal products was estimated to be worth USD120 billion in 2015 and is expected to reach USD7 trillion by 2050.[16] In general, Europe imports from Africa and Asia an estimated 400 000 tonnes of medicinal plants per annum, to the value of USD1 billion.[2,17] The supply of raw materials in Germany was approximately 30 700 tons with a value of EUR84 million (USD 101 938 200) in 2019, with 90% of the plant materials being imported.[18] Pakistan exported therapeutic plant materials valued at USD10.5 million and similarly imported materials valued at USD130 million in 2012.[2] Overall, high-income countries such as Germany, Japan, and USA, with only 15% of the world population, dominated the formal trade with an increase in shared value from 89.1% in 1985 to 92.9% in 1999.[4] In contrast, the combined shared value of low-income countries for the same period decreased from 10.9% to 7.1%.[4] The international status, in terms of demand, of many South African medicinal plant species is increasing. For example, wild ginger (*Siphonochilus aethiopicus* (Schweinf.) B.L. Burtt) and African potato (*Hypoxis hemerocallidea* Fisch., C.A.Mey. & Avé-Lall.) have become more prominent as a growing number of venture companies started utilising them in their formulations.[19]

The national and regional trade is characterised by informal markets (Figure 1) managed by harvesters, hawkers, healers, small traditional medicine chemists, and large traditional medicine markets. The majority of people, between 200 000 and 300 000 in South Africa alone, involved in the value chain of this 'hidden economy' come from rural households and disadvantaged socio-economic backgrounds.[19,20] The informal medicinal plant trade in Africa has a significant socio-economic role as it enables millions of people living in rural areas to generate income.[21] In 1998, an estimated 20 000 tons of South African medicinal plant materials were traded at a value of USD38 million.[21] Thirteen years later, in 2011, the total value of the South African bioprocessing segment, which includes primary and secondary processing of indigenous resources, was estimated at ZAR482 million.[22] Based on the average 2011 currency exchange rate (ZAR7.27 = USD1[23]), this translated to USD66 million. There are, however, variations reported in the value of the medicinal plant trade. For example, other reports estimated that the total value of the trade was ZAR2.9 billion per annum in 2006[24], whereas Myles et al.[25] estimated the value to be approximately ZAR520 million in the same period (2006 exchange rate[23]: ZAR6.78 = USD1). This could be because the trade is mostly informal and, at times, there is supplementation of the plant materials in South Africa with materials from neighbouring countries such as Botswana, Lesotho, Zimbabwe, and Mozambique.[24] Most of the cross-border trade in medicinal plants that was reported between Malawi and other SADC countries such as Botswana, Lesotho, Zimbabwe, Zambia, Mozambique, and South Africa, is illegal[26] and thus poorly recorded. For example, although there was no record of trade in *Mondia whitei* (Hook. F.) Skeels – an endangered species of high demand in South Africa – the government of Malawi reported evidence of trade in this species between the two countries.[26]


**Figure 1:** (a) Traditional medicine products displayed in a small traditional medicine chemist and (b) dried plant raw materials displayed by hawkers in an informal street market.

## Plant secondary metabolites and their global use in medicines

Plant secondary metabolites play an essential role in plants' interaction with the environment, protecting plants against or helping them to survive biotic and abiotic stress.[27] The production of secondary metabolites in plants is dependent on growth conditions and the physiological responses of plants to different environmental conditions.[28] Plant-specific secondary metabolites include phytoalexins, which are antimicrobial compounds synthesised by plants after infection with microorganisms, and may act individually, additively, or synergistically to improve human health.[27,29,30] Secondary metabolites play a role in the signalling and regulation of primary metabolic pathways in plants.[31]

Natural products from plants (phytochemicals) play an important role in drug development processes. The use of some medicinal plants has led to the discovery and isolation of drugs used in the treatment of various human diseases and ailments.[29] For instance, artemisinin from *Artemisia annua* L. has been successfully used as an effective anti-malarial.[28,32] Ellipticine from elliptic yellowwood (*Ochrosia elliptica* Labill.) has been used as an anti-cancer drug.[28] Extracts from African geranium (*Pelargonium sidoides* DC.), which contains coumarins, have promising lead candidates for developing herbal drugs for HIV management.[33] Some of the phytochemicals from African potato corms – including daucosterol, beta-sitosterol, and hypoxoside – have therapeutic properties[34], which have been exploited in the management of HIV/AIDS, cancer, and sexually transmitted diseases[35-37]. *Aloe ferox* Mill. leaf gel, which contains aloin as an active ingredient, and *Lessertia frutescens* (syn. *Sutherlandia frutescens* L.; Fabaceae) containing pinitol and canavanine, were found to be promising in alleviating or preventing non-communicable diseases such as cancer, neurodegeneration, diabetes, and cardiovascular diseases.[30,38] The cited examples demonstrate some crucial roles that plant-based medicines can play in managing chronic and acute diseases. Some plant bioactive compounds used in modern therapeutics are listed in Table 1.

Medicinal plants also have potential in combating or managing pandemic diseases of viral origin due to some plant secondary metabolite antimicrobial (antivirus, antibacterial and antifungal) properties or their attenuating effect on the disease. At least four medicinal plants (*Azadirachta indica* A. Juss., *Eurycoma longifolia* Jack, *Nigella sativa* L., and *Vernonia amygdalina* Delile) showed potential in the management of COVID-19 due to their antiviral, anti-inflammatory and immunomodulatory properties.[39] Four bioactive compounds, which are arabic acid, L-canavine,

**Table 1:** Selected medicinal plants and compounds isolated from their different parts for medicinal use

| Plant origin | Compounds | Plant parts used | Medicinal uses | Commercial products | References |
|---|---|---|---|---|---|
| *Agathosma betulina* (P.J.Bergius) Pillans | Isomenthone and diosphenol | Leaf | Antispasmodic, urinary tract antiseptic, cholera, rheumatism, gout | Buchu oil, Buchu tea, Buchu powder, Buchu tincture | 41, 42 |
| *Aloe ferox* Mill. | Aloeresin A, aloein and aloin | Leaf | Anti-inflammatory, cosmetic applications | Aloe gel, aloe lumps | 43, 44 |
| *Artemisia afra* Jacq. | Eucalyptol, $\alpha$-thujone, ß-thujone, camphor and borneol | Aerial parts | Respiratory ailments, stomach pains | Tinctures, tablets, herbal teas | 44 |
| *Artemisia annua* L. | Artemisinin | Aerial parts | Anti-malaria | Tablets, tinctures, herbal teas | 32, 45 |
| *Aspalathus linearis* (Burm. f.) R. Dahlgren | Aspalathin and aspalalinin | Leaf | Anti-spasmodic<br>Anti-ageing and anti-eczema | Herbal teas | 46 |
| *Camptotheca acuminata* Decne. | Camptothecin | Bark and stem | Anticancer | Tinctures | 47 |
| *Cinnamomum camphora* (L.) J. Presl | Camphor | Wood | Cough, neurodermatitis, fungal infections | Oil extracts, ointments | 48 |
| *Coffea arabica* L. | Caffeine | Seed | Metabolic stimulant | Hot drinks | 49, 50 |
| *Curcuma longa* L. | Curcumin | Rhizome | Choleretic, anti-inflammatory, antioxidant, arthritis | Oil extracts | 51 |
| *Erythroxylum coca* Lam. | Cocaine | Leaf | Local anaesthetic | Medicinal drugs, tinctures | 52 |
| *Eucalyptus globulus* Labill. | Eucalyptol (*Cineole*) | Leaf | Cough treatment | Oil extracts, tinctures | 53 |
| *Gastrodia elata* Blume | Gastrodin | | Anti-convulsion, analgesic | Tuber powder, tinctures | 54, 55 |
| *Harpagophytum procumbens* (Burch.) DC. ex Meisn. | Harpagoside, harpagide, procumbide | Roots | Anti-inflammatory/analgesic | Tuber cuts/powder, tablets, tinctures | 44 |
| *Hypoxis hemerocallidea* Fisch. & C.A. Mey. | Hypoxoside | Root | Anti-inflammatory, anticancer | Harzol® | 44 |
| *Lessertia frutescens* (L.) Goldblatt & J.C. Manning (*Sutherlandia frutescens* (L.) R. Br.) | L-canavanine, arginine, GABA and D-pinitol | Seeds and leaves | Diabetes, fever, HIV/AIDS management | Tablets | 44, 56 |
| *Merwilla natalensis* (Planch.) Speta | Proscillaridin A | Bulb | Antischistosomal, anti-inflammatory and anthelmintic | Unknown | 57, 58 |
| *Pelargonium sidoides* DC. | Prodelphinidin, coumarins | Tuberous roots | Cough, antibacterial and antiviral | Umckaloabo | 44, 59 |
| *Siphonochilus aethiopicus* (Schweinf.) B. L. Burtt | Siphonochilone | Roots and rhizomes | Cough, asthma, anti-inflammatory | Tablets, tuber powder | 60 |
| *Warburgia salutaris* (G. Bertol.) Chiov. | Warburganal, polygodial, salutarisolide, muzigadial, ugandensidial, isopolygodial, mukaadial | Stem bark | Venereal diseases, rheumatism, stomach ulcers, malarial fevers, pneumonia, diarrhoea | Tablets, tinctures | 61, 62 |
| *Xysmalobium undulatum* (L.) W. T. Aiton | Uzarin, xysmalorin, allouzarin, alloxysmalorin | Roots | Diarrhoea, hysteria, syphilis, urinary tract antiseptic, heart failure, malaria, and typhoid fever | UZARA® | 63, 64 |

hypoxoside, and uzarin from *Acacia senegal* (L.) Willd. (syn. *Senegalia senegal* (L.) Britton), *Sutherlandia frutescens*, *Hypoxis hemerocallidea,* and *Xysmalobium undulatum* (L.) W.T Aiton, respectively, all of which are South African medicinal plants, may be exploited as therapeutic agents against SARS-CoV-2 based on their molecular modelling.[40]

Globally, more than 25% of pharmaceutical drugs are of plant origin.[11] Between the years 2000 and 2005, five medicinal plant-based drugs were developed in the USA, and seven more were in clinical trials.[3] In Germany, more than 90% of the citizenry reportedly used herbal medicines alongside pharmaceutical drugs.[15] Alternative and complementary medicine, which relies on extracts from plant materials, gained popularity in America, where more than 62% of the populace was reportedly using plant-based remedies.[19] Close to 50% of the Australian and French populations reportedly used traditional medicine.[16] In China, approximately 40% of the consumed medicine was attributed to traditional herbal medicine.[17] The Chinese government made public their intentions to integrate traditional Chinese medicine into their healthcare system by 2020.[15] The intentions popularised the value of plant-based medicine in treating human ailments. Ayurvedic medicine ('Ayurveda' for short), which is one of the oldest holistic healing systems developed more than 3000 years ago in India, uses over 1200 medicinal plant species and has been included in the national healthcare system in India.[15,16] The national health policy of Bhutan, a landlocked country in South Asia, integrates the traditional medicine system into its healthcare system, with the traditional medicine hospitals providing a free healthcare service.[3] At least 90% of the Ethiopian population was reported to be using herbal remedies for primary health care.[30]

## Cultivation effects on the medicinal value of medicinal plants

The increasing threat of extinction coupled with the scarcity of several medicinal plants, such as *Warburgia salutaris* (G. Bertol.) Chiov. and *Siphonochilus aethiopicus*, as well as the related genetic loss warrants cultivation as a solution.[65] The commercialisation of selected medicinal plants and their medicinal value is driving and directing medicinal plant cultivation research (Figure 2); for example, research on understanding the growth requirements and genetics of medicinal plant species. Cultivation is a crucial element in conservation strategies due to increasing urbanisation, habitat loss, population growth, and industrial developments.[66] Cultivation of medicinal plants can provide opportunities for improving purity and quality, consistency and bioactivity, and biomass production of raw materials.[65] Sustainable production of a number of innovatively developed plant-based products is often hampered by the inconsistent supply of high-quality plant raw materials. Cultivation can improve biomass production for sustainable supply without negatively affecting the bioactivities of the medicinal plants through the manipulation of the growing conditions. For example, the cultivation of *P. sidoides* under well-watered conditions increased the total biomass significantly, without significant alteration in the content of active compounds.[67] Similar results have been reported, where greenhouse cultivation of *P. sidoides* did not result in significant reductions in umckalin concentrations compared to the wild-collected plant material.[68]

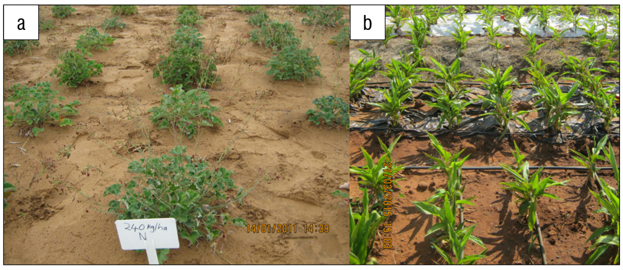


**Figure 2:** Cultivation research: (a) fertiliser application trials on *Pelargonium sidoides* and (b) mulching trials on *Siphonochilus aethiopicus*.

Additionally, in vitro cloned and greenhouse-acclimatised *P. sidoides* plants retained their phytochemical composition, based on phenolic compound profiling.[69] Greenhouse-grown, tissue-culture-derived tubers of *Harpagophytum procumbens* (Burch.) DC. ex Meisn. had a significantly higher total iridoid content than wild-harvested tubers.[66] Active compound concentrations can be affected by a number of factors such as the ecotype, age of plant, size, and season of collection.[66] Although the tubers were collected from different sites, the results indicated that cultivation could maintain the active compound content of the medicinal plant. Application of chemical fertilisers and irrigation improved the concentrations of the potent volatile compounds in *Siphonochilus aethiopicus*.[70] A study by McAlister and Van Staden[71] showed that high levels of nitrogen, phosphorus, and potassium are necessary for increasing the biomass of *Hypoxis hemerocallidea*. However, once the plants are established, the nutrient application can be discontinued to increase the hypoxoside concentrations. This perhaps suggests that hypoxoside synthesis is enhanced when plants are under nutrient stress conditions, providing an opportunity to manipulate the growing conditions by altering the nutrient supply during plant growth.

When bulbs of cultivated *Bowiea volubilis* Harv. ex Hook. f. plants were compared to the wild-harvested ones sold in markets, there was no wide variation in the biological activities.[72] *P. sidoides* extracts from greenhouse-acclimatised plants demonstrated similar antimicrobial and antioxidant properties compared to the extracts from wild-collected plants, supporting the feasibility for large-scale cultivation.[69] The above studies indicate that the bioactivity of medicinal plants could be increased or maintained through the manipulation of agronomic practices.

Although cultivation of medicinal plants is recognised as being important for the development of the formal medicinal plant industry[73] and as a conservation strategy, there remains a paucity of information on the response of several commercially important medicinal plants to cultivation practices. Yet, as illustrated above, different agronomic practices, including irrigation, spacing, fertilisation, and plant growth management, influence not only yield but the quality of cultivated medicinal plants. Hence, the use of standardised and optimised cultivation procedures for each commercially important species becomes important to ensure a consistent supply of good-quality medicinal plant raw materials for the industry. However, some species are difficult to cultivate because of certain biological features or ecological requirements.[74] Other medicinal plants, particularly those whose underground parts are used medicinally, may take a long time to reach maturity, and some growers may not be able to afford to wait more than a year before harvesting due to economic feasibility challenges that may arise with initial capital investment requirement.[74] Research can play a significant role in technology development and transfer as a contribution to the medicinal plant industry and supporting the development of cultivation sites which can create jobs and revive rural economies. Availability of and access to plant materials can also contribute to the preservation of the indigenous knowledge related to various medicinal plants through continued use and generational information dissemination.

## A paradigm shift on the use of cultivated medicinal plants?

Many users of traditional medicine view cultivated medicinal plants with much uncertainty, and this is because they are aware of the effect of the environment on the 'medicinal power' of the plants.[75] Many refer to the risk of 'metaphysical' dangers destroying the 'medicinal power' of medicinal plants cultivated outside their natural environment.[24] For example, nitrogen application resulted in reduced and unstable quantities of the active compounds in *Salvia miltiorrhiza* Bunge compared to the content in wild populations.[76] Such results highlight the need for further investigations into environmental factors or stimulus of secondary metabolites, such as water stress, soil type, and shading, which could influence the active ingredient quantities. Nonetheless, traditional healers and traditional knowledge holders are also aware that traditional health care is at risk because medicinal plants are becoming scarce.[76,77] For example, traditional healers in Zimbabwe recommended the cultivation of two threatened species, *Warburgia salutaris,* and *Alepidea amatymbica* Eckl. & Zeyh.*,* to meet future demands of the species.[78] Furthermore, as many as 98 medicinal plant species were listed as being 'allowed' to be cultivated, whereas 68 were 'not allowed' to be cultivated by traditional healers in KwaZulu-Natal and Gauteng Provinces of South Africa.[9] Cultivation of medicinal plants has been recommended in many platforms, by traditional health practitioners, leading to efforts by the South African government to develop medicinal plant nurseries in various provinces.

Kelatwang[75] reported that 77% of the traditional healers interviewed appreciated a decline in populations of medicinal plants, a further indication of their understanding of the risk of extinction of some medicinal plants. About 69% of traditional healers interviewed in a survey by Dzerefos et al.[79] perceived a decrease in populations of medicinal plants, and the development of medicinal plant nurseries was recommended as the majority (58%) of the traditional healers mentioned that nursery-grown plants were acceptable for use. It seems that traditional health practitioners are now accepting cultivated medicinal plants, as 83% of those interviewed by Nefhere[80] showed interest in cultivating the plants, whereas 80% were willing to buy cultivated medicinal plant species. Similarly, 74% and 83% of the traditional healers and traders, respectively, accepted cultivation as a solution for declining medicinal plant populations.[10] Furthermore, 88% of street traders and vendors of medicinal plants were willing to buy cultivated medicinal plants.[80] Due to the time requirement of cultivation, 58% of the interviewed traditional healers and traders recommended farmers for commercialising medicinal plant cultivation.[10]

On the other hand, pharmaceutical companies need consistency in the quality and market value of herbal products.[30] Appropriate standard operating procedures and proper management of raw materials through cultivation have been advocated as a strategy for quality assurance because medicinal plant materials can be collected from the same area and grown under the same conditions over a period. The optimisation of propagation and cultivation techniques will ensure the supply of good-quality planting materials for local growers and the supply of good-quality harvested materials to the industry.[14] Cultivation of medicinal plants is of great interest to pharmaceutical companies as it allows for the sustainability of supply, reliability in botanical identification of the plant materials, and guaranteed chemical homogeneity. At the same time, it allows for optimisation of secondary metabolite production through manipulation of the growing plants' environment.[14,24,76] Cultivation can also provide an opportunity for increasing the yields of secondary metabolites. As an example, the 'trichome management' technique not only increased biomass yields of leaves and stems and the related glandular trichome density, but it also increased the production and alkaloid (camptothecin) yield in trichomes of *Camptotheca* species.[76] The need for increased cultivation is a reality. For example, in Germany, 750 farmers were reported to be cultivating medicinal plants in a total area of 12 240 ha, and this area was reported to be only 12% of the area required to meet the industry needs[18] as domestic consumption was increasing.

## Recommendations and conclusion

South Africa is faced with challenges in job creation, enterprise development, and revival of the economy. The medicinal plant industry can play a critical role in addressing these challenges as farming is a labour-intensive sector. The medicinal plant industry makes significant contributions to the economies of developing countries, such as South Africa. This contribution is through job creation, rural economy revival, and income generation for small businesses, such as the transport businesses, involved in the value chain. Furthermore, rural communities use medicinal plants for primary health care, as they are affordable and accessible. Cultivation of medicinal plants, which are in most cases harvested unsustainably from the wild, offers opportunities over and above the conservation of the species. These opportunities include more jobs, as more people will be needed to maintain the cultivated fields, increased income, and improved livelihoods of communities. Better prices can also be negotiated because quality and traceability can be guaranteed. However, land, financial resources, and direct market access for rural communities should be addressed as these can also unlock the industry. Research efforts optimising practices for improved yield without compromising quality should be intensified with appropriate funding support for technology development and transfer. In South Africa, different research institutions, government departments – such as the Departments of Science and Innovation (DSI), Trade, Industry and Competition (DTIC), Small Business Development (DSBD), Forestry, Fisheries and Environment (DFFE) – in collaboration with knowledge holders, are already putting in significant efforts in an attempt to formalise the medicinal plant industry. However, there is room for improvements, especially to ease the administrative and compliance burden placed on researchers. Government regulations should be balanced to protect the environment but also to promote sustainable use of natural resources. With enough support, research findings can inform conservation and biodiversity management strategies for effective protection and efficient use of South African biodiversity.

Oversupply of medicinal plant materials can have a negative impact on prices. Therefore, production needs to be managed in relation to market demand. It is also essential to formalise the local medicinal plant trade, especially because traditional health practitioners are starting to accept cultivated medicinal plants so that the contribution to the economy can be recognised. The local trade can be used to develop the emerging growers of medicinal plants, such that they can understand the industry and then graduate to the cross-border trade and ultimately to the international trade where they can supply international pharmaceutical companies.

## Competing interests

We have no competing interests to declare.

## Authors' contributions

M.M.M.: Conceptualisation; writing – the initial draft. C.P.d.P.: Critical review; commentary; writing –revisions. H.T.A.: Conceptualisation; review of the draft. S.O.A.: Critical review. S.N.M.: Inputs in writing the initial draft. K.M.P.: Inputs in writing the initial draft. P.W.M.: Critical review, commentary; writing – revisions.

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# Status quo and sector readiness for (bio)plastic food and beverage packaging in the 4IR

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Single-use plastics emanating from the food and beverage industry are polluting the environment, and there is increasing public pressure to find 'green' solutions to plastic pollution. The introduction of more bio-based and biodegradable plastics (possibly manufactured by disruptive technologies), increased plastic recycling, and enhanced degradation of plastics (micro, meso, and macro) in the environment can holistically contribute to solving the problem for future generations. In order to inform future research, it is imperative that robust background data and information are available. This review provides details about the volumes and categories of food and beverage packaging manufactured and recycled, and available data (qualitative and quantitative) on environmental plastic pollution in South Africa, and to a lesser extent, in Europe and globally. In addition, current and future trends and technologies for recycling, enhanced degradation, and manufacturing of plastics are discussed, with an emphasis on the manufacture of bioplastics.

**Significance:**

Plastic pollution needs to be tackled through a holistic combination of reduced use, enhanced recycling efforts, public education about littering, replacement of selected conventional plastics by degradable alternatives, and enhanced degradation of plastics in the environment.

## Introduction

Plastic pollution of aquatic (marine and freshwater) and land environments has reached alarming levels over the last two decades. In addition, conventional plastics are manufactured from fossil fuels, thus exacerbating the environmental burden.[1] It is therefore imperative that alternatives to recalcitrant single-use petroleum-based plastics are introduced. This paper presents the results of a critical survey conducted by a group of researchers from South African academic institutions forming part of the Technological Higher Education Network of South Africa (THENSA) sub-group on waste management and the circular economy, as well as this sub-groups' Irish research partners. This review is aimed at academics, the private sector, and investors engaged in research, manufacturing and use of plastic food and beverage (F&B) packaging, with an emphasis on bioplastics. It provides information on the status quo of plastic use by the F&B industry in South Africa and identify gaps in the knowledge required to successfully reduce the impact of plastics on the environment. In some cases (for example, plastic production data, recycling data), the situation in South Africa is compared with that in the European Union as an example of the current situations in developing versus developed countries. The way forward in terms of plastics manufacturing is discussed in detail in the context of the Fourth Industrial Revolution (4IR).

The information was obtained from literature, as well as from the opinions of contributing experts from academic institutions, business and industry. A bottom-up approach was adopted to synthesise the most relevant details from the abundance of information available on this topical issue:

1. The volumes and categories of plastic F&B packaging manufactured in South Africa were obtained.
2. Qualitative and quantitative data from articles detailing plastic pollution of land and aquatic (freshwater and marine) environments in South Africa were collated.
3. The categories of bioplastics (Groups I, II, III, IV) and mechanisms (recycling vs enhanced degradation) that could be harnessed to lessen the environmental burden of the most widely used, as well as the most widely polluting F&B industry plastics, were critically assessed, and gaps in knowledge were identified.
4. Furthermore, innovations that have taken place in the manufacture of the identified F&B packaging over the last decade, as well as sector readiness for the 4IR, are highlighted.

Due to the considerable scope of the topic, an in-depth discussion on the synthesis and types of plastic polymers and biopolymers is not included in this review.

## Classification of plastics/bioplastics

The terminology and classification of 'bioplastics' is rather complex (Figure 1) and covers an array of plastic polymers that are either biodegradable (and/or compostable), and/or manufactured from bio-based feedstocks.[2] To lessen confusion, differentiation of bioplastics into 'bio-based', 'compostable' and/or 'biodegradable' plastics is gaining traction. Plastics such as polyethylene (PE) and polyethylene terephthalate (PET) are recalcitrant to degradation and, unlike biodegradable and/or compostable plastics, are well-suited to recycling. They are classed as conventional (Group I) plastics when manufactured from fossil fuel feedstocks.[2] However, when manufactured from biological feedstocks (agricultural biomass, microbial biomass or microbial products), the term 'bio-based' (bio)plastic applies (Group II). The Group III polymers such as polylactic acid (PLA) and polyhydroxyalkanoate (PHA) are manufactured from bio-based feedstocks and are compostable. Group IV polymers such as polycaprolactone (PCL) and polybutylene adipate (PBAT) are manufactured from fossil fuels, but are still typically viewed as bioplastics because they are biodegradable and compostable.[2]

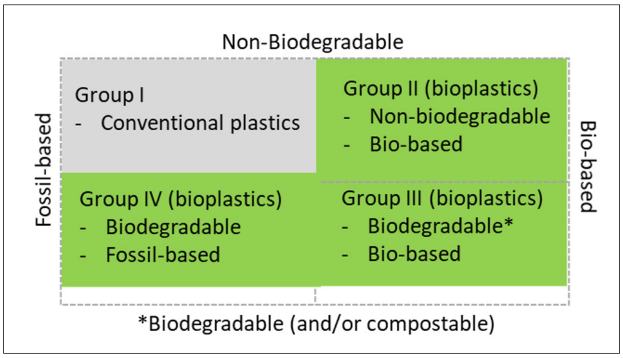



**Figure 1:** Basic classification of plastics and bioplastics (adapted from Jariyasakoolroj et al.[2]).

## Plastics in the food and beverage industry

Food and beverage packaging assists in containing, preserving and protecting the contents during storage and transport.[3] Desirable qualities for F&B plastics include lightweight, durability, chemical resistance, cost-effectiveness, and manufacturing simplicity.[3] Historically, plastics were selected by the F&B industry chiefly on a 'fit-for-purpose' basis using these criteria.[1] However, with the alarming increase in environmental pollution over the past decades, the recyclability and/or biodegradability of single-use plastics has also become a critical consideration[1], and plastic selection should involve a cradle-to-grave approach[4].

Data on the quantities, types, and uses of plastics that are manufactured in South Africa were provided by industry (Plastix 911 2020, written communication, 28 July) (Figure 2, Table 1) and compared with data from Europe. Almost 40% of the 62.8 million tons of plastics manufactured in Europe in 2018 was used in general packaging.[5] In contrast, only around 1.5 million tons of polymer were converted into plastic products in South Africa in 2019, with almost half being used as packaging material, either rigid (60%) or flexible (40%) in nature (Figure 2). Approximately 70% (over 0.5 million tons) of the South African packaging was used by the F&B industry, but in order to arrive at the total annual sum, it was estimated that imported packaged F&B could add ≥50% to these figures (Plastix 911).

The most popular plastics used by the European F&B industry were polypropylene (PP), low-density polyethylene and linear low-density polyethylene (LDPE and LLDPE), and PET at 19.3%, 17.5% and 7.4%, respectively.[5] This differs somewhat from the landscape in South Africa, where estimated amounts were 35% PET, 33% LDPE/LLDPE, 12% high-density polyethylene (HDPE) and 11% PP in 2019 (Plastix 911).

Only 4 of the 13 main polymers that are manufactured in South Africa do not have current applications in the F&B industry (Plastix 911). These are rigid acrylonitrile butadiene styrene (ABS), styrene acrylonitrile resin (SAN), and the flexible polyester and thermoplastic polyurethanes (PUR and TPU). Many of the conventional plastic polymers are manufactured in both flexible and rigid forms (Figure 2), while others are only flexible [nylon, polyester polyurethane (PUR), thermoplastic polyurethane (TPU)] or rigid [ABS, SAN, PET, polystyrene (PS)].

There are a multitude of uses for plastics in the F&B industry (Table 1). As recycling rates of plastics such as PET are already high and set to increase (refer to the section on recycling for details), it is recommended that greater research efforts are directed into low value biodegradable and/or compostable alternatives for plastics that do not lend themselves to recycling and are more likely to litter the environment. For example, clingfilm that is capable of rapid and complete degradation in a variety of environments (including landfill sites) to replace the almost 10 000 tons of polyvinyl chloride (PVC)-based film used annually by the South African F&B industry (Table 1).

## Plastic pollution

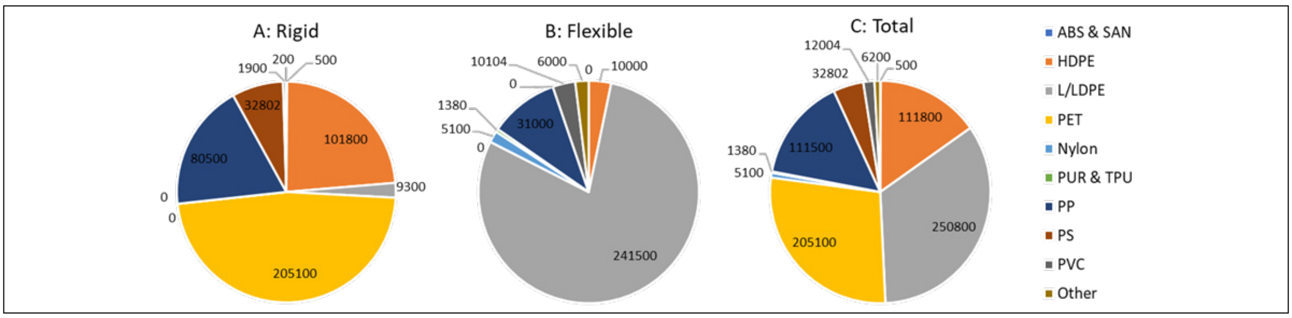
### *Quantification in the environment*

In Europe, close to 60% of plastic waste is in the form of packaging, and the demand for plastic for F&B packaging was estimated to be 8.2 million MT in 2017.[3] Because oceans are downstream of land areas, they are the final sinks of much of the plastic waste generated on land.[6] A comprehensive study conducted in 2017 estimated that 80% of ocean plastic emanates directly from land-based sources.[6] Up to 77% of denser polymers such as PET and acrylics migrate to the sea floor in deep waters, while lower density polymers like PS foam, PE and PP generally float on the sea surface.[7]

Over the decades, plastics in macro (>25 mm), meso (5–25 mm) and micro (<5 mm) forms have accumulated ubiquitously and caused ecosystem stresses in marine, freshwater, and land environments.[8,9]

The current usage of plastic in South Africa is between 30 kg and 50 kg·per person·per year, which is significantly lower when compared to Europe (139 kg/person/year).[10] In total, 22 studies have been conducted since 2015 to determine the extent of plastic pollution in South Africa. Of these studies, 14 focused on abiotic environments (Table 2), and the rest focused on determining biotic accumulation (not included in this review). Only one land-based inland study was conducted[11], whereby macroplastic litter distribution in the shoreline around the Nandoni reservoir in Limpopo was quantified. Most of the litter consisted of F&B packaging, such as wrappers, bottle caps and beverage bottles, as well as plastic bags. In terms of item numbers, PP, PVC, PET and HDPE were the most abundant polymers, with PP constituting >45% by the number of items counted, but PET or HDPE accounted for most of the polymer by weight.

Weideman and co-workers[12] counted floating forms of macroplastic litter by visual observation from bridges spanning major rivers, and definitively identified 20% to be F&B packaging, 6% bottles or bottle tops, and 21% bags or packets. The origin of some of the other items could not be established (24% miscellaneous, 13% PS pieces), but it may also have been the F&B industry. The same authors[12,13] also determined that >98% of the items >0.025 mm filtered from bulk river and dam waters from the Orange–Vaal systems were microfibres. They established that




*Data source: Plastix 911 (personal communication, 28 July 2020)*

*ABS, acrylonitrile butadiene styrene; SAN, styrene acrylonitrile resin; HDPE, high density polyethylene L/LDPE, linear low-density and low-density polyethylene; PET, polyethylene terephthalate; PUR, polyester polyurethane; TPU, thermoplastic polyurethane; PP, polypropylene; PS, polystyrene; PVC, polyvinyl chloride; Other, proprietary Surlyn™ and E/VAL™*

**Figure 2:** Quantities of plastics manufactured in South Africa in 2019 (all figures in metric tons per annum).

**Table 1:** Quantities, products and applications of plastics used by the food and beverage (F&B) industry in South Africa in 2019

| Polymer | Total (tons per annum, TPA) | F&B (%TPA) | Products, and %TPA and applications for each product |
|---|---|---|---|
| **RIGID PLASTICS** | | | |
| HDPE | 101 800 | 55 | Bottles and closures for dairy products, fruit juices, powdered goods such as hot chocolate, custard (32%); crates for bread, milk, soft drinks, beer, fresh produce **(14%); drums >5 L for edible oils and vinegar **(9%) |
| L/LDPE | 9300 | 10 | Caps and closures, peel-off lids |
| PET | 205 100 | 87 | Beverage bottles for carbonated soft drinks, still and sparkling water, energy drinks etc. (75%); bottles and jars for honey, peanut butter, mayonnaise etc. **(7%); sheeting for thermoformed packaging for fresh produce, meat and dairy products, sandwiches, chocolates, prepared meals etc. **(5%) |
| PP | 80 500 | 40 | Closures for beverage and water bottles (4%); buckets for yoghurt, nuts, chocolates, edible oils, shea butter, bulk ice-cream (5%); tubs and jars for yoghurt, margarine, dairy products, prepared spreads, spices, ice-cream (27%); drinking straws, coffee stirrers, cutlery, take-away food containers, re-usable cake domes (4%) |
| PS | 32 802 | 92 | Vending cups (6%); sheeting for thermoformed products – portion packs for yoghurts and condiments (16%); extrusion gassed sheeting for thermoformed packaging for take-away food containers, flat sheeting under cakes, pizzas etc., fresh produce trays e.g. mushrooms, trays for in-store packed meat and chicken, trays/containers for prepared meals etc. (70%) |
| PVC | 1900 | 20 | Sheeting for thermoformed products and die-cut display packaging (20%) |
| Other | 200 | 90 | Polycarbonates in water-fountain refillable bottles, epoxy lining in steel packaging (90%) |
| **FLEXIBLE PLASTICS** | | | |
| HDPE | 10 000 | 60** | Thin barrier bags for fresh produce and cereal inner bags (60%)** |
| L/LDPE | 241 500 | 70 | Bags for frozen vegetables, milk, dry foods (rice, lentils etc.); co-extrusion laminates in barrier packaging for meat and dairy; laminates on paper and board for wettability and sealing |
| Nylon | 5100 | 80 | Co-extrusion layer in barrier films for meat, protein, and dairy products |
| PP | 31 000 | 76 | Biaxially oriented PP for confectionary, sweets, crisps, and chocolate wrappers, laminates for barrier films for food applications (36%); cast film and extrusion blown films for fresh produce such as tomatoes and bananas; laminates on paper and board for improved barrier properties and wettability (40%) |
| PVC | 10 104 | 90 | Industrial cling-wrap for in-store packing of meat, fresh produce, take-away meals etc. (90%) |
| Other | 6000 | 90 | Surlyn co-extrusion layer in form-fill and seal packaging for sweets, cereal and chocolates; E/VAL in co-extrusion layer in barrier films for spices, coffee/cappuccino sachets; E/VAL in packs for ready-to-eat sauces, soups etc.; E/VAL co-extrusion layer in refill pouches for custard, baking powder, beverage concentrates etc. |

*HDPE, high density polyethylene; L/LDPE, linear low-density and low-density polyethylene; PET, polyethylene terephthalate; PP, polypropylene; PS, polystyrene; PVC, polyvinyl chloride; Other, proprietary Surlyn™ and E/VAL™*

***Estimate of HDPE for bags, crates, and drums and PET for bottles, jars, and thermoformed packaging (estimated % split between F&B and other industries).*

larger plastic items and microplastics composed of denser polymers were less likely to be washed out to sea, and more likely to become entrained in dams and riverbanks than the lighter and/or smaller items, particularly microfibres. It has been established that marine microfibres do not typically emanate from F&B packaging, but are composed of plastic from washing synthetic clothing, disintegration of maritime ropes and nets, and degradation of cellulose acetate in cigarette butts.[14,15]

The accumulation of microplastics in sediments is influenced by a number of factors, including the composition, size and shape of the microplastic, the type of sediment, the amount of organic matter in the sediment, the water depth, the flow rate, and the presence of barriers such as weirs or dams.[13,14,16] Chitaka and Blottniz[17] surveyed litter accumulation on five Cape Town beaches and found that of the 2961 litter items per·day per 100, 94.5–98.9% were composed of plastic, and 40–60% of these were F&B packaging, most being snack packets and single sweet wrappers.

Microplastics have been quantified in African beach sediments[15,18], surf-zone water, and open coastlines[18]. Similarly, seafloor macroplastic litter[19] and marine microplastic accumulation[20,21] have been quantified. None of these studies provided insight into specific land-based human littering behaviour, but other studies[22,23] have found that microplastic pollution in more densely populated areas such as harbours and/or urban estuaries was due to land-based litter inputs. In terms of composition, Vilakati and co-workers[24] established that microplastic fragments found on seashores around Cape Town were composed of PE, PET, PVC, PS, polyamide, polyacrylic acid, and ethyl vinyl acetate, with PE>PET>PVC being the most prevalent (Table 1). It is clear that most South African studies (Table 1) have been conducted on microplastic contamination of coastal aquatic and marine environments. In order to inform the type of F&B packing that should be earmarked for research, studies are required to obtain more land-based and inland aquatic litter data.

## *Reducing the environmental impact of plastics through legislation and innovation*

### Plastic recycling

It is estimated that 4900 Mt of the global 6300 Mt of plastics ever produced up until 2017 was discarded, with only 567 Mt (9%) being recycled.[25] The global mechanical recycling rate of plastic waste was estimated to be between 14% and 18% in 2017.[26] South Africa has a relatively well-developed and growing plastic recycling industry, with a higher input recycling rate (46.3%) than Europe (31.1%).[5,27]

The success of plastic recycling in any country or region depends on strong government policies that are well implemented, the availability

**Table 2:** Selected data from studies conducted to determine plastic pollution in South Africa and the surrounding marine environment

| Location | Environmental (abiotic) site | Size and/or type of polymer | Quantification | Reference |
|---|---|---|---|---|
| Nandoni Dam, Limpopo | Populated shorelines | Macroplastic / PP > PVC, PS, PET, HDPE | ~10 to 45 plastic items/25 $m^2$, ~40–700 gdwt plastic/25 $m^2$ ($n$=4 sites) | 11 |
| Orange–Vaal River system | Surface river water | Microplastic (>0.3 mm), Macroplastics (see text) | Wet season: 0.38±1.06 items/$m^2$ ($n$=18 sites)<br>Dry season: 0.27±0.69 items/$m^2$ ($n$=9 sites) | 12 |
| Orange–Vaal River system | Dam river water | Microplastic / hard (85%), flexible (9%) PS (3%) | 0.046±0.166 items/$m^2$ ($n$=5 dams) | 13 |
| Eastern Cape | River sediments | Microplastic / ND | 6.3±4.3 (summer), 160±140 (winter) particles/kg ($n$=21 sites) | 14 |
| South African coast | Beach sediments | Microfibres (< 1mm) | 33–127 microfibres/$dm^3$ ($n$=175 sites) | 15 |
| Braamfontein Spruit | Stream water, sediments | Microplastic / ND | Stream water: 705 particles/kg dwt<br>Sediments: 167 particles/kg dwt | 16 |
| Cape Town | Beaches | Litter (94.5–98.9% macroplastic) / ND | 134 (Muizenberg) to 4421 (Paarden Island) g/day/100 m ($n$=5 sites) | 17 |
| SE coast | Beach sediments, surf-zone water | Microplastic / ND | Beach sediments: 689±348 to 3308±1449 particles/$m^2$<br>Water column: 257.9±53.36 to 1215±276.7 particles/$m^3$ ($n$=21 sites)<br>Harbour water columns: 413±78 to 1200±133 particles/$m^3$ | 18,22 |
| Sub-Saharan Africa | Seafloor of continental shelf | Macroplastic | Seafloor litter: 0.2 to 2.1 items/$km^2$ | 19 |
| KwaZulu-Natal | Sea-surface of coastal shelf | Microplastics / PS, other polymers ND | 3.0±2.9 (summer), 5.5±3.3 (winter) particles/100 $m^2$ | 20 |
| Atlantic Ocean | Sub-surface water | Microplastic / PE, PA, acrylic–PA blends | 1.15±1.45 particles/$m^3$, PE (49%), PA & acrylic–PA blends (43%) | 21 |
| KwaZulu-Natal | Beach and estuarine sediments, surface water | Microplastic / PS, other polymers ND | Sediments: 3.7±5.6 to 160±271 (estuarine), 20±10 to 745±130 (beach) particles/500 mL<br>Surface water: 10±11 to 70±119 particles/103 L | 23 |
| Cape Town | Seashore | Microplastics / PE, PET, PVC, PS, PA, PAA, EVA | PE prevalence: 87.5% ($n$=6 of 7 locations)<br>PET prevalence: 71.4% ($n$=5 of 7 locations)<br>PVC prevalence: 57.1% ($n$=4 of 7 locations) | 24 |

*ND, not determined; dwt, dry weight; PP, polypropylene; PVC, polyvinyl chloride; PS, polystyrene; PET, polyethylene terephthalate; HDPE, high density polyethylene; PE, polyethylene; PA, polyamide; PAA, polyacrylic acid; EVA, ethyl vinyl acetate*

of infrastructure, and, most importantly, industry and community participation. Globally, governments are constantly considering new policy interventions to cut down plastic production, and to reuse and recycle non-degradable plastics. A number of international and South African agreements, policies, and strategies are collectively geared towards reducing plastic pollution by increasing the demand for recycled plastics and improving waste management to reduce or eliminate plastic waste at source.

South Africa's *Waste Act of 2008*[28] stipulates that waste should be separated at household level, and the respective municipal waste collection services should support the waste collection practices. The South African target for recycling is 70%, with the average plastic content of all plastic goods targeted at 30%.[10,27] Specific 5-year targets for reuse, collection and recycling of different forms of F&B plastic packaging have been set in the South African extended producer responsibility regulations. For example, recycling of PET has been set as 54% in year 1 with a stipulated increase to 65% by year 5. In the European Union, the strategy for plastics in the circular economy was adopted in 2018 and ambitious targets are set with a 55% recycling target for plastic packaging by 2030.[5,29]

The key steps in recycling plastic waste into secondary raw materials include collection, sorting, pre-treatment, decontamination and reprocessing.[30] The type of polymer, the ultimate application, the presence of other materials and additives (e.g. caps, coatings, adhesives and inks), the presence of impurities (e.g. dirt/soil/dust and organic residues), and the degree of service-life degradation are all factors that can impact on the suitability of plastic waste for recycling.[31]

The collection and sorting processes for plastic waste vary amongst regions, countries and cultures.[32] A formal collection system and advanced waste management infrastructure exists in the Global North, while in many developing countries like South Africa, waste recycling is less controlled.[33] Nearly 34% of the South African population did not have access to regular waste removal in 2016, and most of the recycling took place within metropoles, with only 3% taking place in rural areas.[34] Collection of plastic waste by the informal sector (waste 'pickers') in South Africa is an important conduit for waste recycling, but is selective in nature because it depends on trade prices and fluctuations in the demand for specific plastic types (mostly higher weight PET, HDPE and PP items).

Sorting of plastic waste is a key factor in recycling as it ultimately controls the quality of the material that will be transported (in bales) to reprocessing sites. Depending on the context (developed vs developing countries) and the origin of the waste, sorting takes place in material recovery facilities, plastic recovery facilities, sorting centres and/or reprocessing facilities.[33] In most countries, including developing countries like South Africa, sorting is manual. However, in some parts of Europe, near-infrared technology is employed, which is more technologically advanced but suffers from some limitations. Near-infrared sensors 'read' only what they can detect, and so false readings may occur, resulting in incorrect sorting when a product is composed of more than one type of plastic, or mixed with non-polymer material/s. The sensors are also blind to 'carbon black' and cannot detect material such as black PET, eliminating it from the recycling lot.[33]

To guarantee high purity levels of sorted plastic, especially for high value polymers such as clear PET and HDPE, near-infrared technology is often paired with other physical sorting processes (e.g sink-float, hydro-cyclone)[35], or, in some cases, with manual sorting. In less advanced facilities, 13–18% of target plastic may be rejected during sorting, with another 12–15% lost due to non-target plastics being discarded.[35]

The recycling lot can be composed of multilayered plastics, flexible plastics (films and bags), black plastics and bio-based plastics, each of which has an associated sorting challenge.[36] It is generally not economically viable to segregate multilayer plastic components, nor plastic film. The latter can account for 40–50% of plastic waste in developed countries, but their low bulk density leads to technical difficulties during sorting and mechanical reprocessing.[31] Bio-based plastics which are identical to their petrochemical-based counterparts, such as bio-PE and bio-PET, can be used as 'drop-in' materials, and therefore can be easily integrated into existing sorting systems. However, contamination of segregated polymer streams with compostable and/or oxo-degradable plastics can compromise the quality of the recyclates[31,33], requiring adaptation of sorting equipment.

#### Enhanced degradation of plastics

Photodegradation, thermo-oxidative degradation, hydrolytic degradation, chemical degradation and biodegradation are the main mechanisms by which plastics degrade in the environment. Composting is a form of enhanced biodegradation. Some compostable plastics can be home composted, while others require more extreme conditions only achievable in industrial plastic composting facilities.[4] Under natural conditions, depending on the type of plastics, the degradation process can be extremely slow. Plastic degradation, by which polymers are fragmented into smaller molecules or elements through hydrolysis or photo/thermo-degradation can be enhanced, for example, by altering reaction conditions or including additives in the polymer mix.[37] These degradation processes and rates are largely incumbent on the type of polymer. For example, studies have demonstrated that: (1) the rate of hydrolysis of PLA and poly(3-hydroxybutyrate) (PHB) can be expedited at higher temperatures and/or pH[38,39], (2) the degradation of PP, HDPE, and LDPE can be promoted by pre-treatment at 80 °C[40], (3) clay additives promote diffusion of water into PLA/clay nanocomposites, thereby enhancing PLA degradation rates[41], (4) addition of 50% ethanol can accelerate PLA hydrolysis[42], (5) nanomaterials such as zinc oxide (ZnO) can be used as natural catalysts to enhance the degradation of polymers[43], and (6) photosensitive polymer additives such as titanium dioxide ($TiO_2$) and ZnO can accelerate photolytic activity associated with light wavelengths from 200 nm to 700 nm [e.g. the photolysis of polybutylene succinate (PBS) by addition of $TiO_2$ nanoparticles)[44].

Some plasticised polymers such as PLA can be biodegraded into intermediate products and may be further degraded (mineralised) into water, carbon dioxide ($CO_2$), methane ($CH_4$) and other inorganic compounds by the action of microorganisms. Key to this biotechnological approach is microbial secretion of extracellular depolymerising enzymes that 'break' the polymers into small enough particles so that they can be internalised into microbial cells where they can be mineralised via microbial metabolic pathways.[37,45] Several microbes capable of degrading different types of polymers have been identified, including PLA biodegradation by *Fusarium verticillioides*, *Penicillium roquefort*, *Amycolatopsis* sp., *Bacillus brevis*, and *Rhizopus delemar*[37]*,* and PHA degradation by a lipase produced by *Bacillus subtilis*[46]*.* Application of functional microbial consortia (i.e. a mixture of microbial strains with different metabolic capabilities) may result in higher degradation rates when compared to the use of single strains, as demonstrated by Pattanasuttichonlakul and co-workers[47] who used a consortium of *Actinomadura* and *Pseudomonas geniculate* to degrade PLA beverage cups.

The biodegradable characteristics of polymers can be manipulated by blending them with other biodegradable materials. For example, Masmoudi and co-workers[45] demonstrated that the biodegradation rate of starch reinforced with cellulose was faster than that of PLA/cellulose fibres. Depending on the longevity required for a particular application, different polymer composites can be used: for example, a starch–polymer composite with a relatively slow degradation rate would be appropriate for single-use F&B packaging. It is thought that the complete lack of functional groups on the extensive inert C-C backbones of conventional plastic polymers renders them recalcitrant to biodegradation. However, some studies have suggested that PE and PVC may be biodegradable, but the authors did not elucidate the enzymatic pathways.[48]

Much remains to be discovered about enhanced plastic biodegradation. Techniques such as protein engineering of enzymes, strain engineering, metagenomics and genome mining are currently being explored. Examples include (1) enhanced degradation of polyurethane by engineered cutinase and polyurethane enzymes[49], (2) the use of genetic engineering to enhance the activity of an enzyme derived from *Bacillus subtilis* for the degradation of PET[50], and (3) the use of metagenomic gene mining to discover plastic depolymerisation enzymes in marine and terrestrial microbial communities[51], and biofilms causing plastic fouling[52], including the discovery of a cutinase and a lipase from two strains of *Pseudomonas* that have been shown to be effective in polyester degradation[53].

Combined physical and/or chemical and biological approaches are also promising. Awasthi and co-workers[54] increased the rate of biodegradation of HDPE by *Klebsiella pneumoniae* by heating the polymer at 70°C for 10 days beforehand. Similarly, Tian and co-workers[55] increased the rate of biodegradation of PS by *Penicillium variabile* using ozonation as a form of pre-treatment. The challenge is now to apply the laboratory findings to the 'real world' in order to remediate our environment through enhanced plastic degradation.

## Manufacturing of (bio)plastics for food and beverage packaging

Bioplastic manufacturing is an emerging and innovative industrial sector that involves the production and processing of biopolymers into biodegradable plastic products. The bio-based polymers can be extracted from biomass, synthesised through intermediaries, or produced by microorganisms. These processes have been well reviewed in the literature and are therefore not discussed in detail here.

### *Bio-based feedstocks*

To reduce the volume of plastics made from fossil fuels, biological materials may be used to synthesise Group II or Group IV (bio-based) bioplastics.[2] Agri-industrial wastes are available in large quantities, making them ideal feedstocks for valorisation. The South African agri-industry generates thousands of tons of residues suitable for downstream bio-economic applications from the processing of millions of tons of sugar cane, grain crops, and fruit each year.[56,57] Feedstocks such as starch can be used to generate plastic polymers by direct chemical processes, while a number of organic feedstocks can be used as substrates for indirect microbial polymer production.[2,58] Some examples of food products and ancillary wastes containing oil, protein, cellulose, starch, hemicelluloses and lignin that can be used to make plastic polymers, either directly or indirectly, are provided in Table 3.

It is challenging to manufacture bio-based plastics with properties comparable with those of conventional plastics. For example, typical starch-based bioplastics have (undesirably) high water affinities and poor mechanical performance when compared to their conventional counterparts.[59] Examples of successful F&B bioplastics include renewable packaging materials from PLA or other bio-polyesters, and cellulose-based polymers sourced from de-lignified wood pulp or cotton linters for coated cellulose films for bread, fruit, meat, and dried product packaging.[60,61] Some cellulose-based polymers are transparent, have high tensile strength, and serve as alternatives to LDPE, HDPE, PS and PET for F&B packaging.[60-62]

**Table 3:** Examples of food wastes and agri-industrial wastes used to produce biopolymers (adapted from Sharmila et al.[58])

| Substrate | Sources |
|---|---|
| Celluloses | Mango seeds, peanut husks, citrus peels, rice, and wheat straw |
| Lignin | Peanut husks, wheat straw, leaves and stalks of corn, sugar cane bagasse, and peels of citrus fruits |
| Fats and oils | Mango seeds, potato waste, peanut seeds, citrus peels, pulse processing waste, coconut waste, waste cooking oil, animal fats |
| Protein | Soybeans, sunflowers and peanuts; cereal by-products e.g. gluten from wheat and maize zein; animal tissues such as collagen, keratin, and gelatin |

## *Conventional plastic manufacturing processes*

### Extrusion and blow moulding

Extrusion is the continuous plastifying, conveying and pushing out of thermoplastic material through specifically shaped dies to make continuous products such as piping, engineering profiles, films, or plates. The semi-finished products can be processed further by thermoforming, and foam extrudates can be produced by adding foaming agents. A way of improving the tensile strength and rigidity of extruded film is by in-line stretching after extrusion, as with biaxially oriented PLA film (BOPLA).[63] In addition, blow moulding can be combined with extrusion.

The most common types of blow moulding are extrusion blow moulding and stretch blow moulding. Beverage bottles have been made from bio-PE by blow moulding, and the Group IV bioplastic PLA is ideal for this process.[64]

### Injection moulding

Injection moulding is the most frequently used form of plastic processing. Components with a variety of shapes and sizes can be inexpensively moulded in large quantities for direct usage. The plastic is melted and injected under high pressure into the mould in an injection moulding machine. Examples of injection-moulded plastics used by the F&B industry include disposable cutlery and beverage cases.[64]

Bio-based polymers can be used for injection moulding provided they have similar characteristics to conventional petroleum-based plastics. It is also common to blend bio- and fossil-based plastics (e.g. PLA with PBAT). Multi-component injection moulding is gaining in popularity with technical advancements in plastic moulding, with a recent study showing that it may be optimised for processing different recycled polymers in micro- and nano-layers.[65]

### Thermoforming

Thermoforming as a manufacturing process uses a semi-finished flat plastic material to produce three-dimensional parts under hot, high-pressure air and vacuum. Typical F&B applications are yoghurt or margarine tubs and drinking cups, and the manufacture of bio-based containers for the packaging of ready-to-eat foods.[66]

## *Plastics and bioplastic manufacturing and recycling and 4IR*

The 4IR is incumbent on a society that adheres to circular economy principles of creating resources instead of generating waste. The plastic industry is set to enter the 4IR using advanced technologies, including additive manufacturing, robots, drones, driverless vehicles, advanced Internet connections (the Internet of Things) and sensors, and decentralised forms of energy, while new technologies such as advanced robotic sorting and driverless collection vehicles may change the landscape of plastic waste management and recycling.[67]

### Additive manufacturing

Additive manufacturing, commonly referred to as 3D printing, is a rapidly developing manufacturing technology that builds objects by sequentially depositing fine layers of material, including plastics, according to digital 3D-model data. It has been referred to as a disruptive technology that has the potential to fundamentally influence many processes. In addition to the potential of additive manufacturing to replace many conventional manufacturing processes, it has prospective impacts on the economy and society by promoting innovative business models, products and supply chains.[68-70]

Ribeiro and co-workers[71] recently reviewed data from life-cycle assessments and proposed a new framework for environmental, economic and social sustainability of additive manufacturing that takes into account different life-cycle phases, methods, technologies and materials. A study by Gebler and co workers[72] suggested that increased use of additive manufacturing could lead to a global energy saving of up to 5% by the manufacturing industry by 2025, but other researchers have contested the energy saving potential of additive manufacturing.[71,73]

In comparison to traditional plastics manufacturing methods, additive manufacturing can be used to fabricate more complex shapes in a more sustainable manner as little to no waste is generated; in addition, the technology lends itself to the use of biopolymers (particularly PLA) and bio-based feedstocks, furthering the 4IR ethos.[67] Additive manufacturing consists of three main phases: modelling, printing, and finishing. Five common techniques are applied for polymeric materials: material extrusion, material jetting, binder jetting, powder bed fusion and sheet lamination.[68] Technological challenges include difficulties with simultaneously printing different materials (e.g. metals with polymers), the lack of low-cost printable materials, and slow print times. Despite the perceived benefits of 3D printing, with the exception of the aerospace and biomedical (parts) industries, the technology has not yet been embraced for large-scale manufacturing, due to a number of limitations including lack of reliability and standardisation, issues with intellectual property, generally slow cycle times and the trade-off between scale and quality.[67,68,71,74] However, it has been widely adopted in the research arena because it is highly customisable and capable of printing complex geometries.[67,68,74]

### Beyond 3D printing

Recent advancements in additive manufacturing have resulted in the creation of a new dimension in four-dimensional (4D) printing and 5-axis 3D printing to generate metamaterial structures with different superimposed structural responses initiated by changes in their operational environments. The applicable 4D printing methods include fused deposition modelling and stereolithography.[75] A major challenge faced by 4D printing is that the mechanical properties of 4D-printed structures may be restricted by the preferred shape and/or functionality of the product. For example, the polymer ratios are critical to sequential folding of the locker structures. The introduction of 'smart' printable materials and a deeper understanding of scale on the structure and function of (bio)plastic products are crucial to overcoming these challenges and advancing 4D printing.[75,76]

### The impact of the 4IR on plastic recycling

New materials, advanced sensors, the Internet of Things, and robots are expected to revolutionise waste sorting and recycling of plastic materials. Albeit with low impact, robots and driverless cars are already being used by the waste industry.[77] Social media and mobile applications are expected to have a significant impact on connectivity amongst formal and informal recyclers. To fast track the new developments in plastic recycling and support the circular economy, innovations on fully robotic sorting and recycling plants, and reuse and redesign of products are considered to be the impacts with the greatest importance. The top six investment priorities to support and enable these are mobile apps, new sensors, social media, big data, new materials and digital utilities platforms.[78]

## Conclusions

Pollution of the environment by single-use F&B packaging made from fossil fuels is of global concern. To mitigate environmental plastic pollution while promoting the principles of circular economies, packaging made from selected plastic polymers that are not readily degradable needs to be recycled, and bio-based and/or compostable/biodegradable plastics need to be introduced on a 'fit-for-purpose' basis. A robust plastics recycling industry exists in South Africa, with non-recyclables being the major contributor to environmental litter. Therefore, as a starting point, research and mitigation measures need to be directed at those plastics that do not form part of the recycling value chain in South Africa. Extended producer responsibility regulations have recently been promulgated and published in South Africa.[79] This legislation should theoretically translate into reduced use of plastics and increased recycling of plastics in South Africa.

From a cradle-to-grave perspective, waste minimisation and energy conservation extend to the manufacturing of plastics. Conventional plastics utilise fossil fuels as feedstocks, thereby contributing to the generation of greenhouse gases. Unfortunately, in most instances, plastics from renewable feedstocks are not comparable with their conventional counterparts in terms of mechanical properties and/or cost and/or recyclability. In the future, additive manufacturing, which has arguably been touted as generating less waste while using less energy, may 'disrupt' traditional plastics manufacturing processes. Together with constant improvements in plastics made from renewable resources, the plastic industry is set to enter the 4IR.

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## Competing interests

We have no competing interests to declare.

## Authors' contributions

P.J.W.: Project management; conceptualisation; writing – initial draft. L.Z.L.: Conceptualisation; writing – initial draft. P.M., S.K., G.D.A., A.R., C.C. and B.F.B.: Writing – initial draft.

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# Biomass conversion into recyclable strong materials

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We review the conversion of waste biomass into recyclable materials using different methods of materials treatment such as thermal, mechanical and chemical processes. Renewable and sustainable biomaterials are increasingly becoming alternatives for synthetic strong materials, e.g. composites. The type of treatment of biomaterial will determine the form to which the biomass is converted and its subsequent applications. It is anticipated that the transformation will produce materials that have superior qualities, properties and characteristics. These include biopolymer materials such as cellulose and hemicellulose, which have all been obtained as products of treatment and extraction from plant materials such as lignocellulose. The main reason for inefficient biomass conversion has been found to be poor manipulation of composite properties during biomass treatment process. The treatment processes are expected to facilitate dehydration, dehydrogenation, deoxygenation and decarboxylation of the bulk biomass materials to target the formation of new compounds that may be used to make strong materials.

**Significance:**

This work demonstrates that plant material, as a solid-state biomass material for strong structural applications such as in biocomposites, is affected by factors that include the alignment of fibres, orientation of fibres, and mass density distribution. However, biocomposite materials have been found to be non-toxic, corrosion-resistant, low-cost, and renewable. They are preferred because the materials possess high thermal stability, are biodegradable and recyclable, and have high biocompatibility, performance, strength, water-resistance, specific surface area and aspect ratio to qualify them for applications including biobricks for construction, slabs for paving, vehicle internal components, ultra-high temperature aerospace ceramics, and energy storage devices.

## Introduction

Global demand for and usage of materials has grown over the past century and the environmental impacts associated with materials management are projected to more than double in the coming decades, with adverse consequences for human health, ecosystems, and the economy. As more materials are used, more wastes are generated and the recycling and recovery rates of these wastes remain low, with most of the waste landfilled or down-cycled and used as lower-value materials.[1] The process of moving biomass waste materials up the green economy hierarchy requires a deep understanding of the nature of the waste materials in terms of their respective physical and chemical properties and characteristics. These parameters determine how the waste materials may be taken up the hierarchy – either as bulk material, broken down into unit components that will be used in different applications, or as a usable form converted through chemical processing of the components of the materials. Biomass may also be converted into recycled materials that have added value with advanced applications either as the bulk material or processed product. Agriculture has been conceptualised into a phenomenon called dual cropping, in which the ability of crops to supply grain for food and then feed and straw or residues for bio-refining is being prioritised. Thus, there is a shift in the breeding of crops to increase grain yield and quality while decreasing straw yield by selection of dwarf-lines, to the practising of programmes that consider harvesting index, a measure of the grain yield relative to total biomass yield.[2]

This work highlights the principal purpose of the waste hierarchy as a way to convert 100% of biomass waste from different waste streams, with the conversion process generating none or the minimum amount of waste, and derive maximum practical benefits from the products that are higher up the bioeconomy hierarchy. Waste hierarchy offers the following advantages: new sources of materials for strong materials fabrication, reduction in pollution, decreasing greenhouse gas emissions, energy conservation, resource preservation, job creation opportunities and stimulation of the growth of green technology.[3] Waste conversion to high hierarchical bioeconomic products is systematic, and serves as an holistic approach to waste management during the life cycle of waste material. Based on the schematic in Figure 1, the waste biomass hierarchy addresses reduction and avoidance, re-use, recycling, recovery, treatment, bulk conversion to strong materials, and safe disposal.[4] An application of the waste hierarchy is interlinked with a circular economy.

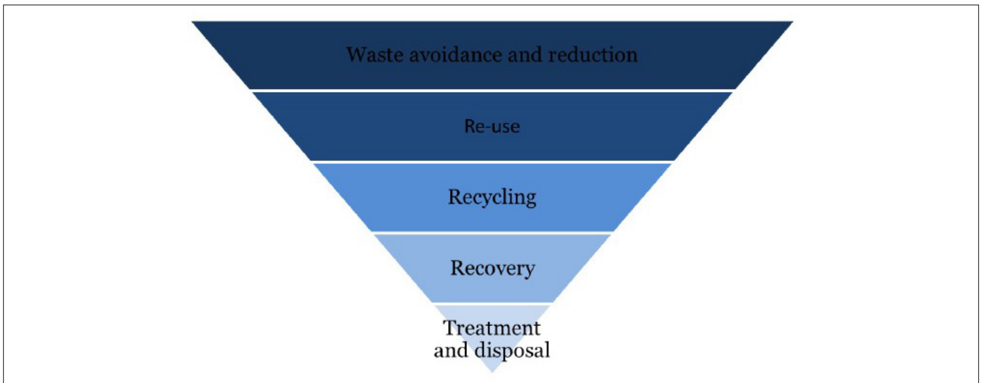


**Figure 1:** Illustration of the waste management hierarchy.[4]

A transition to a circular economy (Figure 2) to increase resource efficiency can lower resource demands and environmental impacts and contribute to economic and social recovery.[1] The circular economy concept involves the use of materials for as long as possible through recycling and material resourcing, as presented in Figure 2. The bio-economy is described as the set of economic activities in which biotechnology contributes centrally to primary production and industry, especially where the advanced life sciences are applied to the conversion of biomass into materials, chemicals and fuels.[5] An effective bio-economy must mobilise large quantities of biomass from a range of resources, including agricultural and forestry residues, and organic fractions of domestic waste.[5]

Lignocellulose is made up of carbohydrate polymers, namely cellulose, hemicellulose and lignin, which is an aromatic polymer. It is the most abundant raw material for bio-based products (Figure 3).[5,7]

Preliminary studies have been conducted on the properties of different lignocellulosic biomasses to determine how to modify biomass for moving it up the hierarchy.[8] It was determined that the use of acidified and non-acidified sodium chlorite to treat wood chips and sugar cane bagasse produced cellulose products that were devoid of aromatic compounds to give high quality lignin and hemicellulose.[9] The moving of biomass up the hierarchy may take a wide range of forms, starting from molecular levels such as in the extraction of active medical or cosmetic active ingredients, to whole or bulk biomass such as in the pulp and paper industry. For example, *Eucommia ulmoides* Oliv. is a widely cultivated medicinal herb with a leaf that is a hyper-accumulator of chlorogenic acid, a type of phenylpropanoid, and it possesses a large number of biological activities such as antibacterial, antioxidant and anti-obesity, and lowers blood pressure. The organic plant material was studied for adsorption and desorption of chlorogenic acid using macroporous adsorbent resins during the extraction of the *E. ulmoides* leaves.[10]

## Treatment and extraction: From soluble to solid-state biomass materials

Biomass from different sources – such as wood, waste plant materials, microalgae and terrestrial energy plants – has been converted into either alternative liquid biofuels or solid-state biomass as bulk or as macromolecules and nanosized particles. Many technical pathways have been developed, including extraction and hydro-treating, pyrolysis, gasification and Fischer–Tropsch synthesis.[11] Biorefinery processes, such as ultrasound and microwave-assisted ternary deep eutectic solvents pre-treatment, were developed to deconstruct the recalcitrant structure of biomass materials for further lignocellulose fractionation and cellulose enzymatic hydrolysis.[12] Similarly, a chemical-free pre-treatment method involving extrusion and ultrasound is also applied to enhance enzymatic hydrolysis of agricultural biomass-rich resources such as rice hull, crop straw and vegetable wastes.[13] Cellulose nanocrystals have also been prepared from oil palm frond by acid hydrolysis preceded by autohydrolysis treatment.[14]

Many other traditional methods have been used previously to extract active materials from different types of plant species biomes. Figure 4 shows the methods of biomass conversion in materials for energy production. Different extraction and treatment processes such as combustion, pyrolysis and gasification can generate the thermochemical conversion of the plant biomass energy. Biological conversion can be obtained through alcoholic fermentation and digestion, while physical conversion occurs by squeezing. The use of methods such as solvent partitioning and Soxhlet extraction prior to enzymatic processing (e.g. cellulases or pectinase) was developed to improve yields and extraction efficiencies of active materials. Latest developments include the advancement of a novel procedure of radio frequency heating-assisted enzymatic

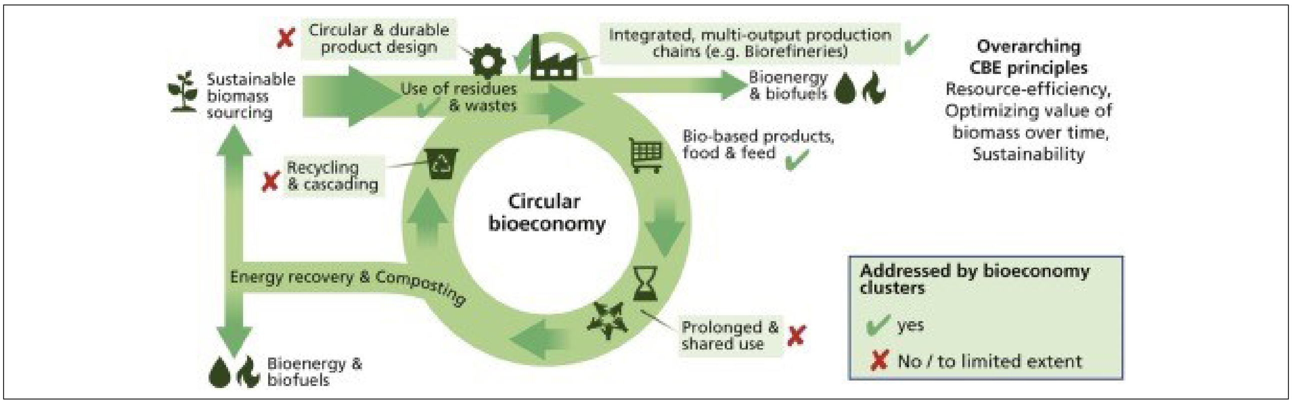


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**Figure 2:** The circular bioeconomy and its elements.

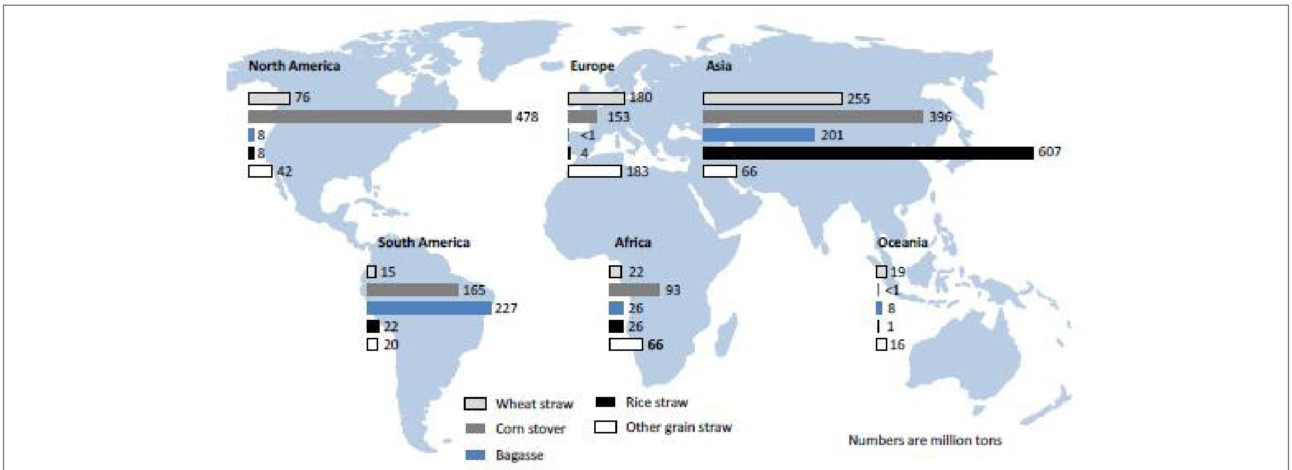


**Figure 3:** Global estimates of lignocellulosic waste materials available for bioproduction. The numbers represent millions of tons.[7]

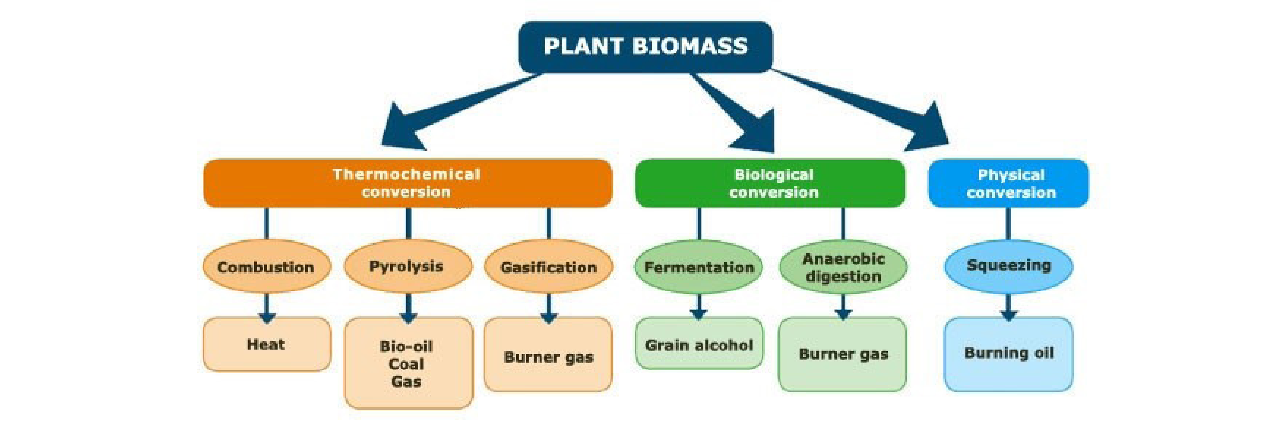


**Figure 4:** Biomass conversion methods for energy materials.[15]

extraction as a more efficient method of solvent extraction of materials such as polyphenolic flavonoids called anthocyanins.[16,17]

The choice of treatment and extraction method for lignocellulose biomass depends on the target material available in the biomass resource of interest. This is because lignocellulose biomass materials contain structural polymeric resins comprising cellulose (40–50%), hemicellulose (20–30%), and lignin (15–25%). Thus, cellulose is the major component in most lignocellulosic resource materials.[18] Several methods of treatment of biomass materials have been applied and reported in the preparation of biocomposites.[19] Methods such as wood fibre and coupling agent extrusion, injection moulding process, lignin precipitation using the lignin-boost process, black liquor Kraft lignin extraction, wet pulp disintegration and TEMPO-mediated oxidation of cellulose beers at neutral pH have been applied in different preparation processes.[19]

## Solid-state biomass for strong materials

There is a need for utilisation of sustainable low-cost carbon-derived materials from abundant and renewable natural resources for various applications. The biomass feedstock can be derived from lignocellulosic materials such as energy crops, agricultural biomass residues, and forest biomass.[20] The biomass-derived materials have strong physical and chemical adsorption properties and are sustainable and environmentally friendly.[21] Given the existence of different plant biomass categories – such as sugar-based biomass, starch-based biomass, oil-based biomass (oleaginous crops), woody and non-woody lignocellulosic biomass and algal/microalgae biomass – more consideration has been given to lignocellulosic biomass in the making of cost-effective solid materials.

A previous study showed that there is no limit to the source of biomass. It is apparent that different materials present different types of biomass that may be used and modified in one or more similar processes to produce valuable materials that are in a high hierarchical position in the bio-economy.[22] Nanosized biomass was prepared from a modification involving bio-inspired self-bonding nanofibrillated cellulose composite. This was done using a simple mechanical thermal rubber milling and the hot-pressing methods. The methods have a response surface procedure for the optimisation of processing variables. This has been applied in binderless biomass materials produced from wheat-straw lignocellulose.[23] Previous studies have revealed that the preparation of activated carbons may be achieved by chemical activation with potassium carbonate ($K_2CO_3$) from five types of nutshells: almond shell, coconut shell, oil palm shell, pistachio shell and walnut shell.[24]

A detailed study on the evaluation of the extraction of sugarcane bagasse and soft wood celluloses with alkali treatment followed by bleaching using sodium chlorite at different times[18], produced bulk solid-state biomass materials used in many different applications such as pulp and paper technologies. There are several targets set to affect, improve, and change physicochemical characteristics of the solid biomass such that there is increased usability, thus adding value and accessibility to biomass materials.[19,25-27] Concerns about global warming and environmental pollution and degradation have triggered a shift in the focus of research institutions towards the development of sustainable, biodegradable and recyclable constituted materials. Biocomposites have potential in the construction industry as renewable building materials and are called natural fibre-reinforced polymers.[28]

The application of solid-state biomass for strong materials includes the high energy density and low-cost lithium-sulfur (Li-S) batteries for energy storage systems, capacitors (or supercapacitors), bio-degradable composite materials, aerogels/or hydrogels. Biomass materials are of great interest in high-energy rechargeable batteries due to the fact that they are sustainable, their use has environmental benefits and, importantly, they are structurally and compositionally versatile with abundant functional groups and many other unique physicochemical properties.[29] An example is a functional biomass carbon with hierarchical porous structure derived from bamboo, which is a low-cost renewable material (Figure 5), for supercapacitor electrode materials.[30] The bamboo-derived porous carbon with boron and nitrogen co-doping was fabricated through successive carbonisation, activation, and heteroatom doping.

**Figure 5:** Bamboo is turned into biomass pellets as stored solid fuel with a performance matched with that of standard coal.[31]

Cellulosic biomass is favoured in the development of aerogel materials because of its biodegradability and sustainability, which is important in their regeneration technique and physical dissolution from non-derivatising cellulose solvents.[32] Chen et al.[30] prepared a highly porous lignocellulosic biomass-derived aerogel directly from a bagasse solution (bagasse dissolved in DMSO/LiCl). Bagasse aerogel displayed sheet-like skeletons with Brunauer–Emmett–Teller surface areas of 185 $m^2/g$ and pore volumes of 0.46 $cm^3/g$.[30] Some biomass materials are derived from cross-linked hydrophilic polymers that are technically referred to as hydrogels. These hydrogels are classified as materials with large volumes of water in their three-dimensional hierarchical structures. Biomass-derived hybrid hydrogel evaporators are built from Konjac galactomannan and iron-based metal-organic components. Their framework is derived from photothermal nanoparticles after being introduced into polyvinyl alcohol networks to form cost-effective hydrogel evaporators.[33] Hybrid hydrogel evaporators have application in heavy metal ions removal and wastewater-purification processes. A cheap biomass, Konjac galactomannan enhances the hydration ability of hydrogels for water activation and provides plenty of hydroxyl groups for the formation of hydrogen and chelating bonds to remove contaminants effectively.[33]

The fabrication of solid-state biomass strong materials involves the use of biomass derivatives that sufficiently and efficiently fuse with biocomposite materials and bind them together to make strong structural materials of different forms. 5-hydroxymethylfurfural (5-HMF) is a material derived from lignocellulose biomass and is convertible, thus promising for biofuels and a variety of useful derivatives which have been previously produced from petroleum. The 5-HMF compound has been considered a fundamental material serving as a mediator between carbohydrate chemistry and mineral oil based industrial materials chemistry.[34] A slightly water-soluble biomass material called rutin – a flavonoid naturally present in many plants, with the highest content of 10.5% found in the dried fruit of the inedible shrub of the smoke tree (*Rhus cotinus*) – is also abundantly found in banana leaves (*Musa balbisiana*)[35] and may be used specifically as a binding material and water-resistant agent in solid-state biomass strong structures.

Figure 6 shows some of the conversions of biomass and the solid-state materials produced through the extraction and treatment processes. Hemicellulose, extracted from sugarcane bagasse using the alkaline-alcoholic method, produced a compact, dense-structured, homogeneously thick, highly water-soluble material which exhibited high tensile strength with an increase in hemicellulose content. However, the increase in hemicellulose content also has the consequential effect of reduced tensile strain and thermal stability.[37] Most biocomposites in solid-state biomass strong materials have found applications in structural artefacts such as pallets, locomotive interior components, construction or building boards, biobricks, 3D printing materials, and ceiling and flooring panels. Thus, the fabrication of these structures is anticipated to develop inherent properties and characteristics that favour the standards of their applications. Strong building biocomposite materials for structural construction are expected to be dense and water resistant and to have high tensile strength, tensile strain and, more importantly, very high thermal stability. The hemicellulose is compact and has a dense structure, homogeneous thickness and high tensile strength – these are the desirable qualities it brings into biocomposites. But it also brings along undesirable characteristics such as increased solubility, low tensile strain and reduced thermal stability.[25]

The shortfalls of hemicellulose call for material modifications or inclusion and infusion of other materials that will improve the undesirable characteristics in the composite matrix. One such biocomposite solid-state strong material is polylactic acid. The polylactic acid material has recently become very popular, mostly in 3D-printing thermoplastic due to its printability, superior biomechanical properties, and biocompatibility. The polylactic acid may be incorporated with sustainable materials or biopolymers such as wood powder, plant fibre, cellulose, lignin, hemicellulose and other biocomposites as a reinforcement material to modify the properties and characteristics of the composite, especially strength, stiffness, and abrasion- and thermal-resistance properties.[38] Detailed studies explored an alternative material to use as a modifying filler towards enhanced inherent properties and characteristics of biocomposites used in the fabrication of solid-state biomass strong structural materials.[37,39-42] Liquorice waste exhibited structural adjustment efficiency in the improvement of the flexural stiffness of biocomposites at a composition range of 5–10% of liquorice waste material. However, the material showed a weakness whereby rapid spore germination took place due to physicomechanical processes that rendered the material vulnerable to sporal invasion.[40]

Wood undergoes massive bulk biomass conversion into a high-value material during pulp and paper making, as shown in Figure 7. The use of paper produces hundreds of millions of tons of wastepaper from which cellulose nanocrystals can be extracted in a high-value secondary fibre utilisation in recyclable strong biomass and biocomposite materials. Methods applied for extraction had an impact on the morphology, properties and characteristics of the cellulose nanocrystals that influenced their binding and filling role in the biocomposites fabricated for strong structural material application.[43]

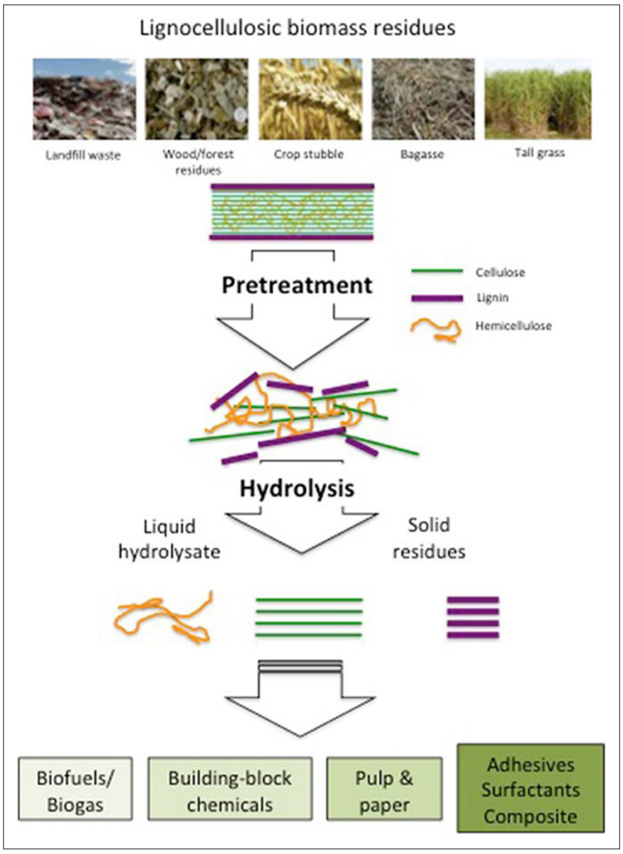


**Figure 6:** Schematic of the conversion process and valorisation of lignocellulosic biomass residues.[36] Hemicellulose is also a good candidate for biocomposites for solid-state biomass strong materials.

Tannin, a natural macromolecular biomass resource mainly found in fruits, seeds, flowers and bark, has found wide application, including in leather tanning. Tannins are characterised by phenolic groups that can form chemical bonds with the functional groups of the matrix in the biocomposites. In leather, the chemical bonds are formed on the carboxyl and amino functional groups along the cross-linking collagen peptide chain of the leather matrix.[42]

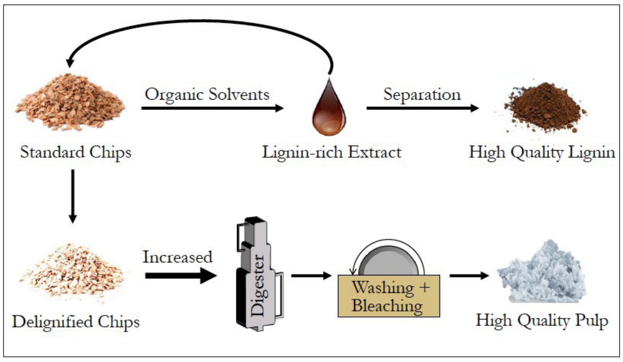


**Figure 7:** Wood bulk biomass conversion into high-quality pulp solid state material.[44]

Recent research in biomass and biocomposites has been driven by a need for the development of sustainable energy, materials and chemicals.[45-47] However, the solid-state biomass strong materials are being managed right from the plant growth in which a high harvesting index is favourable. *Arundo donax* is one of the plants that is being preferentially cultivated as a $C_3$ energy plant and a lignocellulosic biomass feedstock. It is characterised by fast growth and adaptation to severe soil and climatic conditions. *A. donax* has superior biomass qualities due to its chemical composition characterised by a high content of cellulose, hemicellulose and lignin.[11] This material is known to competently substitute conventional synthetic fibres such as glass fibre, carbon fibre and aramid that are widely used as fillers in composites because of their high strength and stiffness. The drive to replace these synthetic fibres is mainly due to their non-biodegradability, high initial processing cost, non-recyclability, and high energy consumption as measured against natural fibres that are biodegradable, renewable, low density, cost effective, non-abrasive, and have high filling levels.[48]

## Mathematical modelling of biomass conversion

Mathematical models are used in the study of a wide range of parameters involving complex processes and mechanisms, especially in science, engineering and geo-environmental studies and analyses. In science, the mathematical models provide an instrument to measure and compare theoretical predictions against experimental determinations and deductions. One such study was on mathematical modelling of biomass gasification in which tar formation threatened the efficiency of the gasification process. Thus, mathematical models were developed to advance the optimisation of gasification reactors in relation to the tar formation mechanism and the decomposition pathways.[49] Complex processes have been deconvoluted using mathematical models for the purposes of optimisation and further process development of the technological applications thereof. Thus, mathematical models ranging from less complex models to highly sophisticated models have been developed for various purposes including process assessment, control and performance evaluation. Single-compound models, kinetic models, and lumped models have been developed for calculating energy and mass transformation.[50-52] Similarly, modelling of anaerobic digestion has evolved radically with variations starting from very simple models that consider digestion as a fermentation process from sugars, to advanced and extended models such as anaerobic digestion model 1 (ADM1).[53]

Mathematical models have been developed to describe processes with a reduced set of parameters, state variables and processes. The anaerobic model number 2 (AM2) is one such mathematical instrument which describes the degradation of soluble organic compounds and is best applied in process control and optimisation.[54] The AM2 was developed by Bernard et al.[55] and the model efficiently reproduced the biological anaerobic digestion process as simulated by the ADM1[54]. Mathematical modelling in biomass transformation processes provides more intrinsic information that may be used to set parametric precedence for experimental determinations, with more access to control and manipulation of internal factors in the processes. Thus, the production of quality target biomass materials may be modelled and achieved; for example, a compromise between a kinetic model, that contains as much tar species as possible to represent lignin devolatilisation, and a mechanism that leads to the formation of tars with minimum reactions stands as a solution for tar simulation during biomass gasification.[56]

## Optimisation and formulation ratios of biocomposites

Materials fabricated from biomass to give solid-state biocomposites for strong materials present a wide range of properties and characteristics. It is anticipated that strong biocomposite materials must exhibit qualities such as non-toxicity, corrosion resistance, high thermal stability, low cost, renewability, degradability, recyclability, high biocompatibility, high performance, high strength, high water resistance, high specific surface area and high aspect ratio.[57] Previous studies have reported on nanolignocellulose/chitin composites with superior mechanical properties and thermal stability fabricated from poplar wood fibre effectively cross-linked with chitin by the simple mechanical thermal rubber milling method.[57] Similarly, layered densified nanolignocellulose/calcium hydrogen phosphate composites and nanolignocellulose/polyvinyl alcohol/titanium dioxide composites were prepared by mechanical thermal rubber milling-water directional assembly and hot pressing.[58,59]

The formulation composition proportions of biocomposites give the materials their inherent intrinsic properties that qualify the materials for applications in solid-state strong biocomposite materials such as in construction and other erectile structures as shown in Figure 8. Contemporary studies on the influence of the ratio of components on properties of wood/thermoplastic polymer composites varying between 10% and 25% wood:plastic, determined that thermal stability and mechanical properties (tensile strength and Young modulus) increased with an increase in hardwood amount.[60] Similarly, investigations into the natural fibre reinforced biopolymers as construction materials were done by comparing the biocomposites with glass fibre reinforced polymers.[61] The natural fibres gave a tensile strength similar to that of glass fibres (of mass density 2500 kg/m$^3$) at a mass density of approximately 1500 kg/m$^3$ – far below the density at the same structural weight as biocomposites, and thus exhibited a higher reinforcement factor.[62] Biocomposites may be hybridised by fusing them with other natural materials that modify and enhance inherent properties and characteristics in materials. Jute is one such material that is fused into solid-state biomass materials for structural applications. A previous study revealed that jute showed more significant acoustic attenuation properties as well as flammability properties than glass fibre in terms of limiting oxygen index.[63]

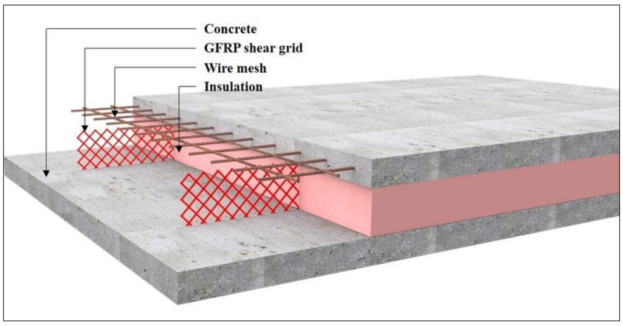


**Figure 8:** Inherent properties of biocomposites as a determinant in applications as strong materials.[64]

Formulations determined by percentage composition of components in biocomposites do not entirely influence the inherent properties of the material as a solid-state biomass material for strong structural applications. Factors such as alignment of fibres, orientation, and mass density distribution directly affect and influence the nature and performance of the fabricated biocomposites. In a study of uniaxial composites fabricated with 30% hemp/yarn composites, hemp fibre orientation (aligned, random, off-axis angle) and alkali treatment were investigated, and it was determined that the aligned alkali hemp/yarn composite exhibited anisotropic mechanical properties including tensile, flexural and impact strengths, lower porosity and water absorption.[65] The main driver for research in biocomposites emanates from their applications in numerous technical fields such as aerospace technology and erectile structures in construction where high strength and stiffness at a low weight are required. It is for this reason that weight-related properties resulting from low densities of the applied matrix systems and the embedded high-strength and high-modulus fibres remain fundamental prerequisites for the tailoring of a composite part to specific demands during anisotropic production.[66] Thus, it may be concluded that weight-related mechanical properties enable biocomposites to be used in applications that are still dominated by glass fibre reinforced plastics.

Studies of formulations of solid-state biomass for strong materials aim to determine the optimum blend ratio of biomass components that must be added to attain a balance between strength and durability requirements for natural fibre composites. This is because the most important variables that determine overall properties of fibres are its structure, microfibrillar angle, cell dimensions, defects, and chemical composition. It was determined that in biocomposite formulations, natural fibres with higher mechanical strength possess higher cellulose ratio, a higher degree of polymerisation of cellulose, longer cell length and lower microfibrillar angle.[67] A comparative study determined that the notched impact strengths of bio-based polyamides with 30 wt.% cellulose fibres were significantly higher than those of polyamides with 30 wt.% glass fibres.[48] This phenomenon was attributed to intensive fibre pull-outs which result in long synthetic cellulose fibres due to friction. It was also observed that there was higher elongation at the break of the cellulose fibres compared to the glass fibres.[68] Understanding the isotropic and anisotropic nature of lignocellulosic materials in the fabrication of biocomposites determines pre-packaging of several properties of the materials that will enable their application in the development of new types of composite materials for constructive biomass strong materials.[62] Use of high aspect ratio biomass is known to significantly change the composite's physical properties in contrast to particulate resin fillers which provide isotropic properties for the material. Different types of biomass in specific compositions, various orientations and lengths, have been exploited in engineering applications to construct devices and structural artefacts with high strength and fracture toughness.

## Conclusions

It was determined that different extraction and treatment processes such as combustion, pyrolysis solvent partitioning, Soxhlet extraction and gasification can generate the thermochemical conversion of the fluidised plant biomass. Cellulose is the major component in most lignocellulosic resource materials. Lignocellulose biomass materials contain structural polymeric resins comprising cellulose (40–50%), hemicellulose (20–30%), and lignin (15–25%). The fabrication of solid-state biomass strong materials involves use of biomass derivatives that sufficiently and efficiently fuse with biocomposite materials and bind them together to make strong structural materials of different forms. Methods such as wood fibre and coupling agent extrusion, injection moulding process, lignin precipitation using the lignin boost process, black liquor Kraft lignin extraction, wet pulp disintegration and TEMPO-mediated oxidation of cellulose beers at neutral pH have been applied in different solid biomass preparation processes. Sugarcane bagasse and soft wood celluloses have been processed to produce bulk solid-state biomass materials. Most biocomposites in solid-state biomass strong materials have found application in structural artefacts such as pallets, locomotive interior components, construction or building boards, biobricks, 3D-printing materials, and ceiling and flooring panels. Strong building biocomposite materials for structural construction are expected to be dense and water resistant and have high tensile strength and tensile strain and, more importantly, very high thermal stability. It was determined that formulations determined by percentage composition of components in the biocomposites do not entirely influence the inherent properties of the material as a solid-state biomass material for strong structural applications. Factors such as alignment of fibre, orientation, and mass density distribution directly affect and influence the nature and performance of the fabricated biocomposites. Thus, it may be concluded that weight-related mechanical properties enable biocomposites to be used in applications that are still dominated by glass fibre reinforced plastics. Thus, understanding the isotropic and anisotropic nature of lignocellulosic materials in the fabrication of biocomposites determines pre-packaging of several properties of the materials that will enable their application in the development of new types of composite materials for constructive biomass strong materials.

## Future research

This review precedes future work that may be designed under focus areas crafted in line with the Sustainable Development Goals (SDGs), covering SDGs 1, 6, 7, 8, 9, 11, 12 and 15. These SDGs fall under a number of niche areas that overlap on different fronts. This review laid foundations for future work in the biomass–biocomposites–bioenergy nexus with a specific focus area in biomass conversion into recyclable strong materials for sustainable cities, smart urbanisation and ecotourism, and green transport. The biomass strong materials will have a high impact in future when fabricated, optimised and applied in materials such as biobricks, bioplastics, bioenergy and biofuels, and biomaterials for wastewater recycling and purification.

The work designed includes making biobricks from coal fly ash and sugarcane bagasse ash. The research will be aimed at innovating current biobrick prototypes to improve their strength for application in the construction of low-cost housing, public infrastructure and modifications in road and bridge construction materials to be ecofriendly and remain sustainable. Sugarcane bagasse is also targeted in the catalytic fabrication of bioplastics that will be used in the manufacture of strong materials including internal motor vehicle upholstery and vehicle mechanical components.

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## Competing interests

We have no competing interests to declare.

## Authors' contributions

F.D.: Conceptualisation; writing – initial draft. L.Z.L.: Supervision; writing – revisions. N.M.: Writing – initial draft. L.M.L.: Writing – initial draft.

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# Viability of whole-culm bamboo construction in South Africa – a preliminary assessment

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We describe literature-based research on the viability of whole-culm bamboo as a construction technology for South Africa. South Africa has one bamboo species considered suitable for construction, namely *Bambusa balcooa*, found in various parts of the country. Quantitative production figures are not currently available; however, local reports indicate that South Africa can expand its bamboo growth industry to meet any possible expected demand. Although the South African bamboo plant has not yet been evaluated in terms of its material properties, engineering design approaches and material properties from the literature indicate that this species is a viable construction material. The limitations for bamboo design and construction are not unique to South Africa but are common to countries involved in bamboo construction. Their experience in overcoming these limitations can be transferred to the use of bamboo in South Africa, making bamboo construction a potentially viable construction technology in South Africa.

**Significance:**

- Whole-culm bamboo can be used as a structural material in buildings and other specialised structures such as bridges, assembly halls, and the like.
- South Africa has a bamboo species that should potentially be suitable for the construction of structures that lend themselves to this type of construction.
- The information given here should allow designers, engineers and technologists to assess the viability of bamboo construction in South African situations.

## Introduction

Bamboo has been used as a traditional building material in many countries for centuries, with reports of bamboo houses in China from 2000 years ago[1] and dams such as the Du Jiang Dam built during the Xia Dynasty[2]. In recent times, bamboo has been made popular by architects such as Simón Vélez (Figure 1) and Jörg Stamm, who operate mainly in Colombia. Although bamboo products, such as floorboards, are popular in South Africa, the use of whole culms in bamboo construction is, practically, not used in South Africa, despite this plant's presence in various parts of the country. In view of the need for innovative and environmentally friendly construction materials and technologies, in particular to meet South Africa's housing challenge, it is appropriate to investigate other possible viable options.

*Image: Namagool7[38] under licence CC-BY-SA 4.0*

**Figure 1:** Bamboo cathedral by Simón Vélez, Colombia.

A literature review to consider the use of whole-culm bamboo construction in South Africa highlighted the lack of coherent structural information regarding bamboo as a potential construction material, particularly from an engineering perspective. Although there are numerous guidelines regarding the construction of bamboo buildings and structures, these focus on construction techniques and are written predominantly by architects or building contractors. Thus, the essential structural properties and design approaches familiar to structural engineers are largely not elucidated in these publications.

Notwithstanding the above, two beneficial sources found were *Designing and Building with Bamboo*, written by Janssen[3] in conjunction with the International Network for Bamboo and Rattan (INBAR), and a series of technical instructional articles by Kaminski et al.[4-7] published in *The Structural Engineer*.

Janssen's technical report[3] collates the practical experience of engineers working with bamboo, together with research programmes into bamboo properties at that time. Aspects covered include the structure of the bamboo plant, propagation, harvesting and preservation. In addition, the mechanical properties of the bamboo culm, together with the typical design calculations required, and aspects such as bamboo connections are addressed. Furthermore, the report touches briefly on the bamboo design standards available at that time and efforts that were then being made towards an international design standard.

In collaboration with the Institution of Structural Engineers (IStructE), Kaminski et al.[4-7] published a five-part technical series on bamboo as a structural material. The series aimed to provide guidelines for the safe design of bamboo structures by collating current knowledge and best practice, based on existing published bamboo and timber design codes. The areas covered were bamboo as a plant, durability and preservation of bamboo culms, design values and equations. The fifth part on bamboo connections has not yet been published.

Information that was available on South African bamboo[8-11] did not include engineering or material properties but focused primarily on bamboo as a source for biofuel and bamboo farming for such purposes. Thus, considerable local and practical research would still be needed if bamboo construction were to become an accepted and standard construction technology in South Africa. Such research would need to establish the engineering and material properties of South African bamboo, as well as provide input towards developing a national design code for such construction.

We aimed to evaluate whether whole-culm bamboo construction is a viable construction technology for South Africa and provide critical information sourced to highlight the areas requiring further research and investigation in the South African context.

## Research methodology

The research was primarily desktop in nature due to the lack of bamboo structures and bamboo construction in South Africa. A comprehensive literature review and document analysis were conducted on bamboo and bamboo construction, mostly focused on South Africa and surroundings. Limited technical data were available, and therefore information was also collected from online news articles, project reports and Internet websites of organisations such as INBAR and NBASA (National Bamboo Association of South Africa). The primary Internet search engine used was Google Scholar, using search terms such as "bamboo", "South Africa" and "Bambusa balcooa". Each document or article was reviewed and critiqued regarding the validity, reliability and applicability of the information presented. For the news articles and websites, this entailed tracing the original source of information to verify the details. Where references were provided in the reports, the original references were scrutinised to verify the information. Furthermore, the current status of the information presented was interrogated, and the sources contacted for updated details.

Due to the general lack of bamboo structures in South Africa, the only site visits conducted were to local areas of bamboo growth in the Western Cape, and to a bamboo farm in Vredendal, in the Western Cape.

## Bamboo in South Africa

An assessment of bamboo resources in 2005 by the Food and Agriculture Organization (FAO) of the United Nations and INBAR, found that Africa had 7% of the world's bamboo resources[12], comprising approximately 2.7 million hectares of bamboo forest[13]. Some of the species are indigenous, being endemic due to natural processes. Others are considered introduced or naturalised species, having been brought to an area by human action or intervention. After 10 years without direct intervention by humans, introduced species may be considered to be naturalised.

South Africa has one indigenous species, namely *Thamnocalamus tessellatus* or 'bergbamboes' (Figure 2). This species is a loosely tufted bamboo that grows in dense clumps. It is used to construct gates and screens and for walking sticks, implement handles and spears.[14] It is found in the mountains of South Africa, Lesotho and Swaziland, at elevations of 1500–2000 m.

*Image: SANBI[39] under licence CC-BY-NC*

**Figure 2:** *Thamnocalamus tessellatus* – an indigenous South African bamboo species.

South Africa also has a naturalised species, namely *Bambusa balcooa*, also known as 'Giant bamboo', which is said to have been introduced into South Africa in 1653 by the Dutch East India Company.[15] This species grows in the KwaZulu-Natal, Mpumalanga, Gauteng, Eastern Cape and Western Cape Provinces (Figure 3).[16,17]

**Figure 3:** *Bambusa balcooa* at Canal Walk Shopping Centre, Western Cape.

Several commercial initiatives to grow bamboo have been initiated in South Africa in the past 10 years, which are described in detail by Scheba et al.[14]. Some, such as the Green Grid Beema Bamboo Project in KwaZulu-Natal (Barathi N 2020, written communication, October 20) and the pilot projects at Ndakana, Uitenhage and Chintsa by the Eastern Cape Development Corporation in the Eastern Cape, have been abandoned due to drought, land ownership disputes, community conflicts and a shortage of funds (Figure 4).[14]

One successful initiative is the Kowie Bamboo Farm, owned by EcoPlanet Bamboo Southern Africa and situated in the Eastern Cape (Figure 5a). Two bamboo species are grown on the farm[18], namely *B. balcooa*, the preferred local species, and *Oxytenanthera abyssinica*, a drought-resistant species thought to have been introduced to South Africa from Zimbabwe[15]. Although the last planting was reported to have been done in 2014, no culms have been harvested to date.

A further successful initiative is a farm called Lateral Project Solutions, based in Vredendal in the Western Cape (Figure 5b). Several bamboo species such as *Phyllostachys edulis*, *Bambusa vulgaris* and *O. abyssinica* are being grown to determine which ones adapt best to the local climate.[15] Although the plants are growing well, no findings have been published at this stage.

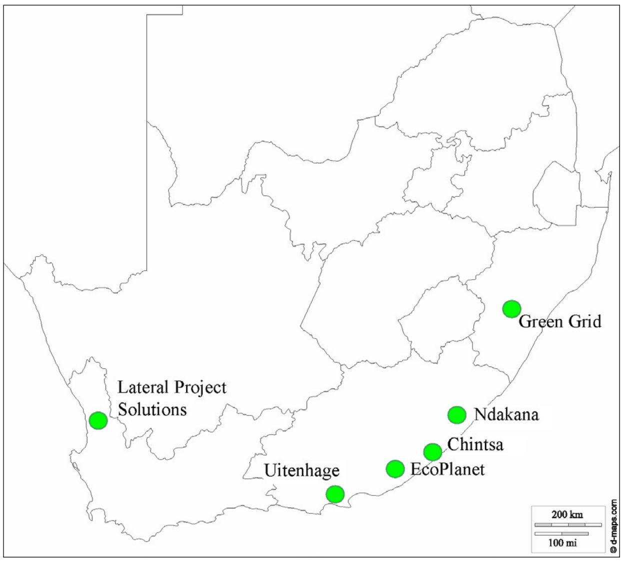


*Image: ©Andreas Scheba; adapted from Scheba et al.[14] with permission*

**Figure 4:** Map of commercial bamboo projects and activities in South Africa.

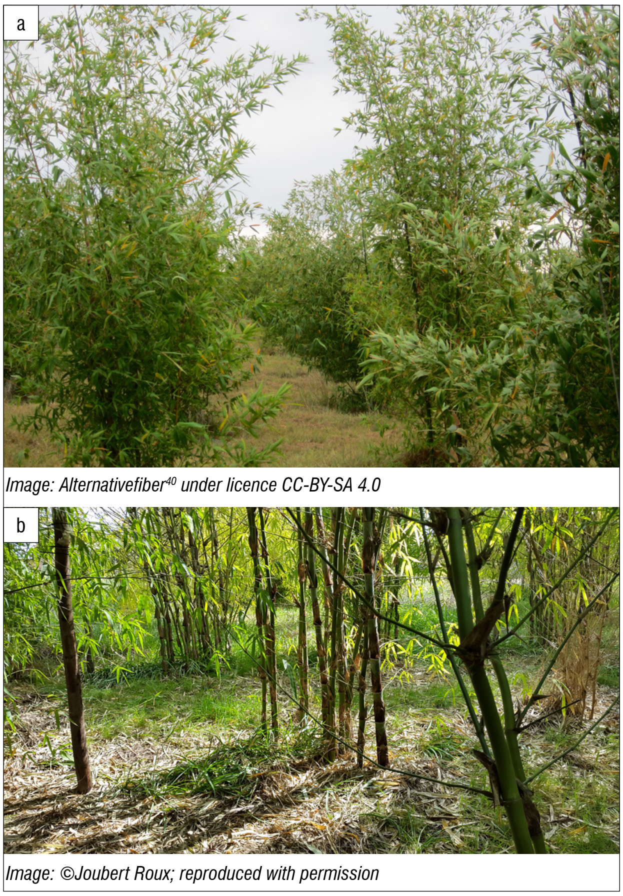


*Image: Alternativefiber[40] under licence CC-BY-SA 4.0*

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**Figure 5:** (a) Kowie Bamboo Farm, Bathurst, Eastern Cape, South Africa. (b) Lateral Project Solutions Bamboo Farm, Vredendal, Western Cape, South Africa.

Thus it can be seen that certain bamboo species can grow and thrive in the South African climate, provided that they receive sufficient water and care, and could therefore be a source of construction materials.

## Anatomy and growth of southern African bamboo

A bamboo plant consists of the visible stems and leaves and the underground root system. The culm or stem is the portion of the bamboo plant found above ground. The culms are generally straight and hollow and vary in size, diameter and texture, depending on the species. At particular spacings along the culm, there are transverse diaphragms or nodes, which are solid (Figure 6). These diaphragms provide a pathway for nutrients and prevent buckling and cracking of the walls by providing cross-sectional stiffness. The cells in the culm length (i.e. the internode) are oriented axially along the length of the culm, with no radial cell elements. Most internodes are hollow, although some species have solid internodes, often referred to as 'male bamboo'. Thus, in the species with hollow internodes, the only transverse connection in the culm is at the nodes or diaphragms.[3,4] The outermost skin or layer of the bamboo culm wall is covered with a waxy layer of silica, which protects the culm from water ingress.[4]

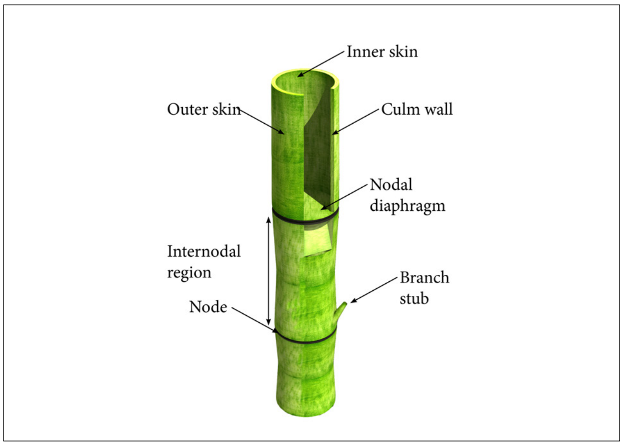


*Image: ©Sebastian Kaminski[4]; reproduced with permission*

**Figure 6:** Parts of a bamboo culm.

The macroscopic characteristics of bamboo vary along the height or length of the culm, with the culm diameter and wall thickness decreasing from the base of the plant upwards.[3] The cross-section of the culm is roughly circular to elliptical, tapering towards the top of the plant. Shorter culms taper more strongly, while longer culm lengths taper less, and as a result, these are often preferred for building purposes, as this results in straighter culms with less change in diameter.[19]

Although other bamboo species growing in South Africa could be used for structural and construction purposes, *B. balcooa* is currently considered the most suitable. This is a clumping species with sterile seeds, and as such, is not regarded as invasive. It grows to an average height of 20–30 m, with a culm diameter of 80–150 mm, a wall thickness of 25–50 mm and 200–400 mm internodal spacing.[20] Although this species reaches maturity between 5 and 8 years, as with other bamboo species, it can be harvested at 3 years of age for construction purposes.[10,14,18]

*Bambusa balcooa* requires approximately 5000 litres of water per year per clump[21] (irrigation or precipitation), which equates to roughly 14 litres per day. This amount is similar to the quantity of 14.5 litres per day reported by Roux (Roux J 2020, oral communication). The amount of water provided influences the growth rate. As such, Scheba et al.[14] recommended that bamboo be grown in South Africa in areas of high rainfall, such as the Eastern Cape and KwaZulu-Natal, which have a mean annual rainfall of 600–1000 mm per year.[22]

## Quantitative requirements for bamboo construction in South Africa

South Africa currently imports a variety of bamboo products. In 2012, 68 t (metric tons) of raw bamboo was imported, increasing to 141 t in 2020.[23] This increase in imports indicates an increased demand for bamboo products in South Africa[14], although this is small when compared to world imports such as China, which imported 21 398 t of raw bamboo in 2020. The most common uses of bamboo in South Africa were fencing, flooring, cladding, home products such as chopping boards, and household furniture.

South Africa exported 494 t of bamboo flooring and 15.6 t of bamboo paper based articles in 2020.[23] The difference between import and export values of bamboo appears to indicate that the difference is partially made up of locally grown bamboo.

The South African Bamboo Interim Steering Committee, formed in 2012, produced a strategy document for the promotion of bamboo in South Africa.[13] Included in this document was a study done by the South African Agricultural Research Council on the potential for bamboo production in South Africa, in which possible land areas were grouped into four classifications, based on the physio-biological requirements of the plants, namely high, moderate, low and marginal. They reported that South Africa had 421 715 ha with a high potential for bamboo production, representing 0.5% of the total South Africa surface area. Of this high potential group, KwaZulu-Natal had the largest suitable area (188 023 ha), while the Western Cape had the smallest (6214 ha). It was noted in the report that this represented the potential for bamboo production and not the available land.[13]

Furthermore, 1 590 076 ha was considered moderately suitable, 2 374 967 ha was considered to have low suitability, and 4 604 471 ha was considered marginally suitable. These hectares represented 1.9%, 2.8% and 5.4% of the total surface area of South Africa, respectively. A summary is provided in Table 1.

**Table 1:** Potential bamboo production areas in South Africa[13]

| Province | Province area (ha) | Percentage of province suitable for bamboo production[a] | | | | Total (%) |
|---|---|---|---|---|---|---|
| | | High | Moderate | Low | Marginal | |
| Eastern Cape | 16 896 598 | 0.05 | 0.37 | 0.57 | 0.54 | 1.5 |
| Free State | 12 982 516 | – | 0.03 | 0.26 | 0.77 | 1.1 |
| Gauteng | 1 817 830 | – | – | – | 0.78 | 0.8 |
| KwaZulu-Natal | 9 435 133 | 0.22 | 1.07 | 1.06 | 0.80 | 3.1 |
| Mpumalanga | 7 649 471 | 0.17 | 0.32 | 0.76 | 1.16 | 2.4 |
| Limpopo | 12 575 396 | 0.04 | 0.06 | 0.10 | 0.84 | 1.0 |
| North West | 10 488 168 | – | – | – | 0.42 | 0.4 |
| Western Cape | 14 010 998 | 0.01 | 0.01 | 0.02 | 0.06 | 0.1 |
| %Total RSA surface area | | 0.50% | 1.9% | 2.8% | 5.4% | |

[a]*Adapted from Bamboo Interim Steering Committee[13] with permission*

Based on the 2012 import information (68 t of raw bamboo), the Bamboo Steering Committee calculated that 865 ha of bamboo farming would be sufficient to produce that amount of bamboo locally, representing only 0.2% of the high potential areas, based on the assumption that the required bamboo varieties can be grown in South Africa, and that 1 ha of bamboo plantation could yield 20–40 t of bamboo per year. If the demand for bamboo increased, such as would be expected if bamboo were used as a construction material, it was estimated that utilising up to 1% of the high potential area would be sufficient to satisfy total demand. Thus, it appears that South Africa could produce sufficient bamboo locally to supply current and future bamboo needs, without the need for importing any bamboo.[13]

As yet, no figures are available as to the amount of bamboo produced locally by the various growers and nurseries. Once these figures become available, it will be possible to verify the above assumptions regarding the amount of bamboo produced and thus whether South Africa can meet the bamboo demand with locally grown bamboo.

## Design and construction using South African bamboo

Many factors can affect a building project's success or failure, not all of which can be quantified. In order to ensure success, it is necessary, inter alia, to understand the limitations inherent in the chosen building material and to select the appropriate mitigations.

For design and construction using bamboo in South Africa to be successful, the structural engineering issues that arise when building with bamboo must be addressed. These can be categorised into three main areas, namely:

- Geometry and anatomy of the bamboo
- Material and engineering properties
- Analysis, design and modelling aspects

### *Geometry and anatomy of the bamboo*

Bamboo culms do not have a regular circular shape, being closer to an ellipse. In addition, the diameter and wall thickness of the culms vary along their length, and the internodal lengths vary from base to top.

The variations in physical geometry present problems with the construction of bamboo structures. When building with steel, timber or concrete, the member sizes can be matched so that connections can take the same form and aesthetic. With bamboo members, either each connection should be unique, or connectors should be used that can be adapted to varying diameters and sizes. In addition, the culms are hollow, which results in little or no support in the middle of the culm to transfer the loads, particularly shear loads. Thus, it is recommended that bamboo members be designed to carry mainly axial loads, with shear loads applied at the nodes.[4]

As described earlier, *B. balcooa* has typical geometrical characteristics such as a culm height (internodal spacing) of 200–400 mm, culm diameter of 80–150 mm, and wall thickness of 25–50 mm. However, the actual dimensions are specific to each plant and batch of material, and would need to be determined prior to design and construction.

The curvature of the culms can also affect a structure's regularity, where the columns and beams could be slightly out of plumb. This curvature can be overcome by using a mortar or plaster overlay on the frame or walls to mask the variations, similar to the bahareque construction method.[24] Alternatively, the culms can be selected to minimise this curvature and allow the slight curvature to add to the structure's natural look.

The bamboo culms are covered with a layer of silica on the outside. Although this waxy layer protects the culm from ingress of water, it also presents a problem during construction, as the outer layer of silica on the culm walls reduces the friction of the culm surface. This condition necessitates that connection designs do not rely on the culm's frictional resistance to function, but instead assume frictionless surfaces which require positive mechanical joints.[25]

### *Material and engineering properties*

Although engineering and material properties are not readily available for South African *B. balcooa* plants, this species grows in other parts of the world, and reports have been published on its properties. These values can be used as a guideline for South African bamboo properties. However, it is essential that the local plants are comprehensively tested to assess their specific engineering and material properties prior to any detailed structural designs. Such testing would have to build up sufficient statistical data for design calculations to achieve adequate material factors, or factors of safety.

### *Physical and mechanical properties*

Salient physical and mechanical properties are summarised in Table 2. The variability in the quoted values can be ascribed to different testing

**Table 2:** Summary of *Bambusa balcooa* properties

| Density (kg/m³) | Modulus of rupture[a] (MPa) | Compressive strength[b] (MPa) | Shear strength[c] (MPa) | References |
|---|---|---|---|---|
| 783 (green) | 65 (green) | 47 | – | Bureau of Indian Standards[26] |
| 720–850 | 116–173 | 48–81 | 10–13 | Naik[30] |
| 570–740 (green)<br>790–850 (dried) | 62–85 (green)<br>70–93 (dried) | 39–51 (green)<br>51–57 (dried) | – | INBAR[20] |

[a]*Measured transversely in flexure*
[b]*Measured parallel to the grain*
[c]*Measured perpendicular to the grain*

procedures and the geographical location where the plants were grown. Also, it is known that the properties of bamboo culms vary along the length of the culm as well as with the age of the culm. Details were not available regarding the testing procedures, and thus it can be assumed that the variable values result from the factors mentioned above.

It should be noted that the properties extracted from the Indian National Building Code[26], as indicated in Table 2, are results obtained from tests on culms of 6 m lengths and are not the properties recommended for design. This code recommends using a safety factor of 4 for flexure and 3.5 for compression. This would result in design stresses of 16 MPa and 13 MPa for the modulus of rupture and maximum compressive strength, respectively.[26]

The International Organization for Standardization (ISO) released two standards for bamboo design in 2004, subsequently updated in 2012, namely ISO 22156:2004 – Bamboo structural design[27] and ISO 22157:2004 – Determination of physical and mechanical properties of bamboo[28,29]. Although these standards do not provide design values or properties, they provide guidance for design procedures.

Both Janssen[3] and the ISO design standard[27] recommend using a safety factor of 2.25 to calculate allowable design stresses. It is unclear why the Indian code recommends a higher safety factor, but this could be based on the expected reliability and variability of the properties found in the local species of bamboo.

Janssen[3] suggested rule-of-thumb ratios to determine properties of bamboo culms based on their density, to be used in preliminary designs (Table 3). Using a density of 783 kg/m³, as indicated by the Bureau of Indian Standards in Table 2, the ratios provide theoretical ultimate stress values of 110 MPa for the modulus of rupture and 74 MPa for the compressive strength. Applying a safety factor to these values reduces them to values similar to those reported by Naik[30].

**Table 3:** Rule-of-thumb ratios according to Janssen[3] and resulting stresses for mechanical properties of bamboo (assuming an average density of 783 kg/m³)

| | Modulus of rupture | Compression | Shear |
|---|---|---|---|
| Ratio[3] | 0.14 | 0.094 | 0.021 |
| Stress (MPa) | 110 | 74 | 17 |

Thus, it is recommended that the ratios be used for preliminary designs only and that the species to be used in construction be tested to determine more precise and reliable values prior to final design and construction. Furthermore, we recommend the use of the safety factors suggested in the international design standard for bamboo, namely ISO 22156.[27]

## Density

*Bambusa balcooa* has a density generally between 720 kg/m³ and 850 kg/m³ (Table 2), somewhat higher overall than South African pine[31], which varies from 450 kg/m³ to 800 kg/m³, and is considerably lighter than steel at 7800 kg/m³.

The lightness of this material is advantageous in conventional construction, as the low mass will reduce the load on the foundations, which can consequently be smaller and less costly. In a seismic situation, the light weight will result in lower downward and lateral loads, resulting in a smaller seismic load on the structure. Furthermore, the bamboo culm's flexibility and ductility allow the structure to absorb vibrational forces with minimal damage.

However, in high wind situations, more weight in the building is preferable to counteract the wind forces. In areas where moderate to high wind forces occur, heavier foundations or sturdier structures would improve the structure's stability and assist in counteracting the wind forces. In addition, the superstructure (and foundations) should be designed and constructed to function as a unit, thus increasing the resisting mass of the building. According to the Beaufort wind scale, an empirical measure of observed wind speed[32], South Africa is considered a moderate wind range area with the highest wind speeds occurring in the Northern Cape. Thus, although some modification to increase the weight of the foundations or buildings would be necessary, this would not be considered a limiting factor.

Typically, industrial warehouses and long-span roofs are designed and constructed from structural steelwork because concrete beams become too bulky, whereas steel can still be slender for the same properties. Conventional gang nail timber trusses can span to approximately 9 m; thereafter, laminated timber beams become preferable, which would increase the cost of the project. Bamboo is lighter than steel, and trusses can be formed to span these lengths and longer, such as those designed by Asali Bali Engineers in Indonesia and surrounding areas (Figure 7), which span up to 20 m.[33]

*Image: ©Olivier Betting[33]; reproduced with permission*

**Figure 7:** Bamboo warehouse by Asali Bali Engineers.

## Durability

According to the available literature, untreated bamboo structures typically have a lifespan of 10–15 years[3], being susceptible to attack by fungi and insects. In addition, bamboo deteriorates when exposed to moisture. However, with preservation, this lifespan can be extended to approximately 25 to 30 years[3,5], depending on the exposure conditions.

Typically, buildings are designed for a 50-year lifespan; thus, bamboo's shorter lifespan could limit this material's usage or restrict its usage to temporary or semi-permanent structures. In addition, the cost of the preservation of the bamboo culms will increase the cost of the structures built in terms of total lifetime cost.

Further research is required to establish whether the lifespan of bamboo culms can be extended to 50 or more years with suitable preservation, focusing on the bamboo species found in South Africa.

## Failure modes

Columns typically fail by crushing or by buckling, such as when the load applied to the longitudinal axis of the column exceeds the compressive strength of the material of the column (crushing) or when the load leads to deformation of the column, leading to instability (buckling). When bamboo columns fail due to a compressive load, the lateral bond fails between the longitudinal fibres, and the circular form of the cross-section no longer provides resistance. In addition, bamboo tends to fail in shear by splitting and cracking, such as when loads are applied at bolted connections (Figure 8), due to the hollow structure, lack of cross fibres in the internodes and low circumferential tensile strength.

*Image: ©Kent Harries[41]; reproduced with permission*

**Figure 8:** Splitting failure due to bolted connections.

In order to overcome this, bamboo structures should be designed to avoid internodal point loads, transferring all loads at the nodes of the culm. Alternatively, specialised steel connections may be designed to transfer the loads, strengthening the bamboo culm's nodal points, such as those developed by Christoph Tönges.[34]

This failure mode of bamboo presents a modicum of safety, as a failure in this way does not indicate complete failure of the entire culm but instead indicates imminent failure. In this way, a margin of safety is available to escape from the structure prior to collapse.

## Analysis, design and modelling aspects

As mentioned, the variations in physical geometry present problems with the design. Most structural engineering formulae and design software assume that the members being designed are constant along their length, with isotropic material properties. Not only do the culms vary along their length, but due to the composition of the fibres, they are also anisotropic, having different material and engineering properties in the longitudinal, radial and tangential directions. Several guidelines are available in the literature to overcome these issues, such as assuming average properties along the culm's length and using properties from test samples when designing detailed connections. Kaminski et al.[7] suggest that a series of measurements should be taken and equations used to calculate the various properties based on these measurements. In a similar vein, Silva et al.[35] proposed using graded elements incorporating the measured material properties at integration points for use in a finite element method analysis, specifically when designing for local stresses near supports, pin connections or holes.

In contrast, Sharma[36] modelled a bamboo portal frame in two dimensions, using beam elements with appropriate geometric and material properties to represent the individual culms. Thus, the variations in the culm properties could be modelled with varying beam elements. Sharma compared the theoretical results from the calculations with results from an experimental model and concluded that the theoretical model had captured the fundamental behaviour of the proposed portal frame.

Irregular geometry could also result in irregular structures. The irregularities can either be minimised by careful selection of the culms to be used or incorporated as part of the aesthetics of the structures. All these aspects, of course, have implications for the overall and detailed design of the structures.

## Guidelines and codes for bamboo construction in South Africa

There are currently no South African design codes for the design or construction of bamboo structures. As mentioned earlier, INBAR has published several guidelines and material values that can be used for the preliminary sizing and design of such structures, such as *Designing and Building with Bamboo – Technical Report 20*[3] and *Design of Bamboo Scaffolds – Technical Report 23*[37]. The technical series by Kaminski et al.[4-7], also mentioned earlier, presents the design process using a limit state approach.

Codes from other countries or sources may also be used, such as the National Building Code of India[26] or the International Code for Bamboo, ISO 22156 and 22157[27-29]. These were discussed previously, as were the recommendations of authorities such as Janssen[3].

As bamboo construction is not yet an accepted form of building construction in South Africa, as defined by the NHBRC (National Home Builders Registration Council), additional tests and calculations would be required to obtain building permits, such as load-bearing capacity and behaviour in fire. Although reference can be made to the ISO standards in a rational design, these calculations would still be required.

Many Eastern countries, such as India, China and Japan, have a history of bamboo construction and have adapted their construction and design methods to suit the vagaries of their local bamboo species. These adaptations can be transferred in principle to bamboo construction in other countries where bamboo construction is uncommon, such as South Africa.

## Conclusions

Although there are possibilities to use other bamboo species for construction, there are two species in South Africa currently considered suitable, namely *B. balcooa*, a naturalised species, and *Beema bamboo*, a clone of *B. balcooa.* Unfortunately, some of the attempts to grow these bamboo species have failed, and the remaining growers and nurseries do not have quantitative production figures. However, local reports indicate that South Africa has the potential to expand its bamboo growth industry to meet potential demand.

The engineering and material properties of *B. balcooa* as found in South Africa have not yet been established. Testing would be required to determine these design parameters before bamboo design and construction could become commonplace in South Africa.

As bamboo design is not included in any South African design code, it would be necessary to use codes and guidelines from other countries, such as ISO 22156: Bamboo – Structural Design.

The limitations for bamboo design and construction are not unique to South Africa but are common to other countries involved in bamboo construction. Their experience in overcoming these limitations can be transferred to the use of bamboo in South Africa, making bamboo construction a viable building technology in South Africa.

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## Competing interests

We have no competing interests to declare.

## Authors' contributions

S.R.: Conceptualisation; research; writing. M.A.: Conceptualisation; student supervision; review of writing and revisions.

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# Causality between challenges, availability, and extent of use of local building materials

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The promotion of sustainable practice in construction has resulted in a renewed focus on local building materials (LBMs). However, existing studies have not provided an extensive understanding of the challenges in the use and awareness of the availability of LBMs. In this study, we examine the challenges in the use and awareness of the availability and environmental performance of LBMs in South Africa. Based on a review of related literature, a questionnaire survey was undertaken to collect data from stakeholders in the construction industry. Structural equation modelling was conducted to validate the causality between the constructs. We found that the negative impacts of the challenges in the use of LBMs significantly reduce if stakeholders are aware of the environmental performance of LBMs in South Africa. The extent of the use of LBMs will increase with an awareness of their environmental performance and availability. Acquisition of the technical knowledge associated with LBM-based construction processes and recognition of the use of LBMs for building projects in building requirements and regulations are recommended.

**Significance:**

The study provides an understanding of the challenges in using LBMs linked to construction stakeholder awareness of their availability and environmental performance. This understanding will promote the use of LBMs in the construction industry and provide a valuable reference for stakeholders in decision-making and policymaking on their use.

## Introduction

Building construction is resource-intensive, and it is associated with environmental problems such as global warming, ozone layer depletion, and waste accumulation. Building construction accounts for one sixth of the world's freshwater consumption because the requirement for mixing water for building materials, such as concrete, is approximately 1 trillion litres per year.[1,2] As a result of construction activity, fresh, clean water is getting scarcer every day.[1,3,4] Besides this intense water consumption, building construction also requires the mining of large quantities of raw building materials, which results in extensive deforestation and loss of topsoil.[1,2]

The majority of buildings are constructed using conventional and imported building materials.[5-9] Conventional building materials are those materials which have been accepted and used for a long time in a locality.[7] The production of conventional building materials has a direct impact on natural biodiversity as a result of the fragmentation of natural resources and severe ecological damage.[5] Imported building materials have huge transport and import duty costs.[9] These materials negatively impact the environment and economy because they are costly and consume much energy in the manufacturing process.[6] However, the mitigation of the negative impacts of these building materials is possible through the use of local building materials (LBMs).[6,8]

LBMs refer to building materials that are non-conventional and enable sustainable building practices. LBMs have been referred to as green building technologies or sustainable building materials.[10-13] Chan et al.[10] posited that materials for green roof technologies, solar technologies, and prefabricated construction technologies are examples of green building technologies. The term 'green' encompasses sustainable and alternative materials because it describes the practice of using healthier and more resource-efficient building materials.[13]

The promotion of sustainable practice in construction has resulted in the development of LBMs.[14] This development aimed to improve the environmental or sustainability performance of building materials, through reduced water usage, greater energy efficiency, improved indoor quality and minimisation of construction waste.[15,16] The benefits attributed to the availability of LBMs contribute to the competitiveness of building contractors, optimise building performance, and make buildings' use more predictable for an extended period. Darko et al.[17] noted that the availability of LBMs has led to unique building products that have good marketing opportunities in Ghana. The availability of LBMs has also been linked to the possibility of meeting the ever-increasing demand for buildings, stemming from population growth and over-urbanisation.[11,18] However, LBMs are facing challenges in penetrating the market.[18]

Several studies have provided evidence that there are challenges to the use of LBMs. Durdyev et al.[11], Ahn et al.[15] and Mesthrige and Kwong[19] focused on the challenges of alternative and sustainable design and construction. Chan et al.[10,13] and Nguyen et al.[18] investigated the challenges of adopting green building technologies. These past studies suggest that imported materials are preferred to LBMs, owing to the lack of awareness of the availability and environmental performance of LBMs.

However, these studies did not give an extensive analysis and understanding of the challenges to the use of LBMs caused by lack of awareness of the availability and environmental performance of LBMs. Hence, it becomes vital to investigate specifically the challenges in the use of LBMs associated with the lack of awareness of their availability and environmental performance amongst construction industry professionals. According to Chan et al.[10], Darko et al.[17], Shen et al.[20], and Mesthrige and Kwong[19], there is a need to understand the challenges in the use of LBMs. Thus, in this study, we aimed to facilitate the understanding of the challenges linked to construction stakeholder awareness of their availability and environmental performance. This understanding will promote the use of LBMs in the construction industry and provide a valuable reference for stakeholders in decision-making and policymaking on their use. To achieve this aim, we asked: What is the relationship between the challenges, availability and use of LBMs by construction stakeholders?

We aimed to answer this research question through the following objectives: (1) to determine the extent and pattern of the use of LBMs; and (2) to investigate the causality between environmental performance, challenges, and extent of LBM use by construction stakeholders.

## Literature review

### *Environmental performance of LBMs*

Numerous studies have reported lower environmental impacts of LBMs. For example, Windapo and Ogunsanmi[16] investigated the perception of construction stakeholders of the environmental performance of LBMs and concluded that construction stakeholders perceived the LBMs to be not environmentally sustainable, despite the claims of their manufacturers. Bribián et al.[21] reported that materials such as hollow concrete blocks, stabilised soil blocks, or fly ashes could save 20% of the cumulative energy over a building's life cycle and concluded that buildings constructed with wooden structures require less energy and emit less $CO_2$ during their life cycle than buildings with other types of structures. However, the global availability of timber might be an issue, questioning the extent of the real sustainability of the material.[22]

The findings of these studies suggest that the sustainability assessments of building materials must be based on specific indicators that provide information about the environmental impacts of the materials.[23] The findings also suggest that a standard life cycle assessment (LCA) must be used to assess and compare the sustainability of conventional building materials (CBMs) and LBMs. According to Estokova and Porhincak[24], the use of a standard LCA as an indicator of the sustainability of LBMs and for the assessment of the environmental impacts of CBMs is needed to achieve an accurate assessment of the performance of building materials and to develop a uniform and standard baseline for both CBMs and LBMs. Several studies have used the LCA as a uniform and standard baseline for CBMs and LBMs.[25-27] For example, Monteiro and Freire[25] conducted an LCA of CBMs and LBMs for exterior walls; Reza et al.[26] studied an LCA of CBMs and LBMs for flooring systems; and Pargana et al.[27] undertook a LCA of CBMs and LBMs for thermal insulation materials. The objective of an LCA of LBMs is to ascertain their environmental friendliness and to enable the optimal selection of environmentally preferred materials.[28]

Various authors have suggested different indicators for assessing the embodied emissions of building materials. Table 1 provides a list of building materials, divided into categories of low and high embodied energy, and their corresponding carbon emission values. Table 2 presents a summary of the indicators available in the literature which assess the embodied emissions of building materials.[29-32]

Embodied energy describes the energy required for the extraction of raw materials, transportation and manufacture of building materials, as well as the energy incurred during their life cycle. This includes repair through to end-of-life disposal.[28,33] It is essential to perform an embodied energy analysis of the building materials in the LCA because building materials consume nearly 40% of global energy annually in their life cycle stages and because building materials represent more than 50% of the embodied energy in the building.[21,33] A LCA enables the selection of low energy-intensive materials, limits greenhouse gas emissions into the atmosphere, and reduces the cost of materials.[33]

Energy is being used at an unsustainable rate because the manufacturing, construction, and operation process of building materials are energy-intensive.[1] Cabeza et al.[28] note that the energy consumption of building materials starts from production to demolition. This suggests that embodied energy consists of both initial embodied energy (energy consumed during manufacturing and transporting the building materials) and recurring embodied energy (energy consumed during construction, demolition, operation, recycling, and renovation).[34] Initial embodied energy is pollution-intensive and in large quantities as a result of a great deal of energy consumed during extraction, processing, and transportation of building materials.[35] In the same vein, initial embodied energy accounts for 50% or more of the total embodied energy of building materials.[36] Examples of high-energy building materials are aluminium, cement, concrete, steel, copper, PVC, glass, baked bricks, timber, crushed rock, gravel, and sand.[21,30,31]

**Table 1:** Building materials with low and high embodied emissions and energy

| Building materials with high embodied energy | | Building materials with low embodied energy | |
|---|---|---|---|
| **Material** | **Carbon emission values (kg $CO_2$eq per unit)** | **Material** | **Carbon emission values (kg $CO_2$eq per unit)** |
| Steel reinforcement | 1.49 | Sand | 0.01 |
| PVC (polyvinyl chloride) | 2.22 | Sun-dried bricks | 0.24 |
| Fibreglass | 2.60 | Reinforced concrete | 0.36 |
| Air-dried sawn hardwood | 2.61 | Lightweight steel | 0.88 |
| Plastics | 2.70 | Cement | 0.89 |
| Rubber | 3.18 | | |
| Galvanised steel | 3.29 | | |
| Copper | 3.83 | | |
| Synthetic rubber | 4.02 | | |
| Gravel | 4.32 | | |
| Clay bricks (fired) | 5.50 | | |
| Aluminium | 11.89 | | |

*kg $CO_2$eq per unit describes, for a given mixture and amount of $CO_2$, the emission that would have the same global warming potential when measured over a specified timescale.[59,60]*

**Table 2:** Indicators for assessing the embodied emissions of building materials

| Indicators for embodied emissions | References |
|---|---|
| Abiotic depletion, acidification, eutrophication, global warming potential, ozone layer depletion, photochemical oxidation, freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, human ecotoxicity | Monteiro and Freire[25] |
| Climate change, acidification, summer smog, nitrification, heavy metals | Coelho and de Brito[29] |
| Emission of heavy metals, eutrophication, water consumption | Gonzalez and Navarro[30] |
| $CO_2$ emissions, CO emissions, $SO_2$ emissions, NOx emissions, dust, waste generation, water depletion | Li et al.[31] |
| Global warming, ozone layer depletion, acidification, eutrophication, airborne suspended particles, construction waste, photochemical smog, waterborne toxicities, waterborne suspended substances, water depletion, fossil energy source depletion | Li et al.[31], Chowdhury et al.[32] |
| Energy consumption, acidification potential, human toxicity potential, aquatic ecotoxicity potential, aquatic sediment ecotoxicity potential, terrestrial ecotoxicity potential | Chowdhury et al.[32] |

Buyle et al.[34] established that there is a strong link between the environmental impact of building materials and cost implications. This must be established because building materials have economic significance as well.[28] Embodied cost as a concept has been described in several ways – including as the total economic cost in the life cycle of a product[21], and the total cost of acquiring, installing, operating, maintaining and disposing of building materials[28]. Despite its importance, according to Buyle et al.[34], the embodied cost of building materials is hardly ever taken into account in LCA models.

As noted by Fahimi et al.[35], reducing the embodied emission, embodied energy, and embodied cost of building material will ensure its sustainability. LBMs enable the reduction of embodied emissions by supporting the use of cost-saving construction technology such as modular designs and standardised components.[37] LBMs are generally lower in embodied energy because they require less processing and transportation.[35] Chen et al.[36] argued that LBMs are better suited to climatic conditions, and their use supports the local economy. Maintenance consumes a significant portion of a building's operating budget. The cost of maintaining conventional building materials includes the costs of labour, cleaning, equipment, and replacement of the item.[38] However, LBMs offer low maintenance over the building's lifetime. This supports a reduction in the embodied cost of building materials. Other ways by which building materials can be made sustainable or by which LBMs reduce embodied emission, cost, and energy include recyclability (LBMs can be reused in their entirety), biodegradability (LBMs naturally decompose when discarded), reusability (LBMs may easily be extracted and reinstalled), and reduced toxicity (LBMs are less hazardous to construction workers, building occupants, and the environment).[39,40]

## *Challenges to the use of alternative building materials in construction*

The challenges to the use of LBMs can be categorised into technical challenges, environmental challenges, policy challenges, cultural challenges, and economic challenges.[41]

### Technical challenges

Technical challenges describe the practical difficulties and unsatisfactory systems that affect the adoption of innovation or innovative systems.[42] Technical challenges constitute a set of practical challenges for the use and installation of LBMs in general.[43] Chwieduk[41] noted that the technical part of the adoption of LBMs pertains to the roles of human beings in the utilisation or installation of these materials. This suggests that the lack of technical understanding and technical know-how on the use of LBMs has to be addressed to ensure the implementation of sustainable practices in the construction industry.[15,44] This is because the technical understanding and know-how of LBMs enable the development of transferable skills, the uptake of technical roles, and leveraging of competencies in the use of LBMs.[45]

Technical challenges have been found to affect the use of LBMs in construction. Zhang et al.[14], O'Neill and Gibbs[46] and Lam et al. [43] have identified problems. Such problems include unclear and incomplete technical standards for LBMs, lack of tools for assessing the performance of LBMs, lack of technical knowledge on the use and installation of LBMs, and immaturity of the technology employed for developing LBMs. Other challenges include the ineffective application of LBMs, technical difficulties during the construction process, unfamiliarity with the design and construction of buildings with LBMs, lack of reliable research into the properties of LBMs, and lack of training and education for developers, contractors, and policymakers. The other significant technical challenges are lack of skilled labour in building with LBMs, lack of databases and information on LBMs, unavailability of rating and labelling systems for LBMs, difficulties in providing technical training for construction workers, higher requirements for handling LBMs, and incompatibility with other building components.

### Environmental challenges

The use of conventional building materials in building construction has been associated with environmental issues such as thermal discomfort and climatic change.[44] Many studies have reported on the environmental challenges to the adoption of LBMs.[10,11,13,20,43,47] These environmental challenges include special needs arising from certain climatic and geological conditions, lack of availability of pilot projects, unavailability of reliable LBM suppliers, limited knowledge of the environmental performance of LBMs, lack of information on the effect of LBMs on building occupants' health and comfort, low environmental awareness and consciousness, lack of green ratings for buildings, and the unwillingness of suppliers to exchange environment-related information with manufacturers. All studies highlight the need for an awareness of the environmental performance of LBMs when they are adopted and used.

### Policy challenges

The use of LBMs is, to a large extent, dependent on governmental policies and industrial stakeholders' policies.[20] Several studies[13,47-51] have identified governmental policy as one of the primary ways of promoting the use of LBMs. LBM-friendly policies are required to attract construction stakeholders to the use of LBMs, as well as to stimulate and ensure the development of LBMs. Additionally, LBM-friendly policies are useful in raising awareness and facilitating the adoption of LBMs, as well as leading the construction industry towards being a more environmentally friendly sector. LBM-friendly policies usually come in the form of legislation, planning control, government involvement as a client, and code development.[41] However, the non-availability and ineffectiveness of policies inhibit the use of LBMs.[20] Specifically, policy challenges in respect of the lack of enforcement of the use of LBMs on new projects, complex certification procedures for LBMs, lack of subsidies and tax reduction for LBMs must be addressed. Also, it is vital to tackle the lengthy planning and approval process for LBMs, lack of regulations, lack of importance attached to LBMs by industry stakeholders, lack of promotion for LBMs, lack of codes for LBMs, rigid requirements, poor information dissemination and publicity, and unavailability of institutional frameworks for implementing the use of LBMs.

### Cultural challenges

The ideas, traditions, beliefs, and social behaviour of society are collectively referred to as socio-cultural factors, and they affect the choice of building materials in so many ways.[51,52] For example, Chiu[52] identified 'social well-being' as a significant determinant of the preference for sustainable materials. The study describes 'social well-being' as the motivation to sustain the socio-cultural values of the society. This suggests that the decision to use LBMs is strongly related to the socio-cultural characteristics of the society in which the LBMs are to be introduced. Understanding the socio-cultural challenges that affect the use of LBMs is imperative because the socio-cultural characteristics of a society determine the preferences and attitudes of its inhabitants towards new products such as LBMs.[53] Authors such as O'Neill and Gibbs[46] and Liedtke et al.[54] have identified the socio-cultural challenges in the adoption of LBMs to include stakeholders' reluctance to use them, the tendency to maintain current practices, the tendency to resist change, a lack of practical cooperation and working relations amongst different stakeholders, distrust of LBMs, unavailability of approved LBMs, risk and uncertainty involved in adopting LBMs, lack of tested and reliable LBMs, fear of employee turnover and joblessness, the inconsistency with best practice, the fragmented nature of the building supply chain, lack of attractiveness of LBMs to building occupants, and lack of client interest.

### Economic challenges

Contractors usually procure building materials based on the lowest price.[20] Hwang and Tan[12] contend that cost is the most significant challenge impeding the use of LBMs. Mulligan et al.[48] attribute this to the fact that contractors are mostly concerned that the use of LBMs will erode their financial gain. Kats et al.[55] conclude that, compared to conventional building materials, the use of LBMs brings a maximum extra cost of 4%. In the same vein, Zhang et al.[14] concluded that the cost of the use of LBMs is higher than that of conventional building materials. This implies that the use of LBMs constitutes an economic or financial risk, which may lower the economic benefits of projects. However, Mesthrige and Kwong[19] note that LBMs significantly lower operating costs by 30%, maintenance costs by 9%, enhance property value by 8%, and boost return on investment by 7%.

There are several significant economic challenges to the use of LBMs established in the literature. The major ones are low profitability for contractors, unavailability of LBMs in the local market, lack of information on costs and benefits of using LBMs, the high initial investment for LBMs, high additional cost, long payback periods, and high market prices.[11,12,49]

### Theoretical framework

Based on the literature review, a theoretical framework of the causality between the awareness of the environmental performance and availability of LBMs, challenges and extent of the use of LBMs was developed, as shown in Figure 1. The framework explains that an awareness of the environmental performance of LBMs contributes to their adoption in construction projects. The availability of LBMs impacts the challenges to the use and extent of use of the LBMs. The challenges to the use of LBMs were conceptualised as technical, environmental, policy, cultural, and economic challenges. The positive environmental performance of LBMs was theorised to be low embodied emissions, low embodied energy, and low cost. The environmental performance regarding low embodied emissions was based on previous findings that air pollution and greenhouse gas emissions are released as a result of the production and transportation of building materials.[16] LBMs are expected to have low embodied emissions because the products do not undergo secondary manufacturing and need no transportation, as materials are sourced locally. The extent of use of LBMs was conceptualised as present and future use of LBMs on projects. The theories that the research is designed to test are:

H1: There is a relationship between the challenges to the use of LBMs, the extent of awareness of their environmental performance, and the extent of use of LBMs by construction organisations.

H2: There is a relationship between the challenges to the use of LBMs, the extent of awareness of their availability, and the extent of use of LBMs by construction organisations.

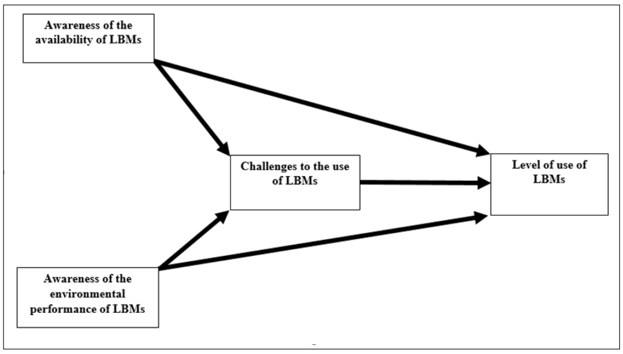



**Figure 1:** A research framework of the causality between the awareness of the environmental performance and availability of local building materials (LBMs), challenges and extent of the use of LBMs.

## Research methods

A questionnaire survey was undertaken to find out about construction industry stakeholders' views on awareness of the environmental performance and the availability of selected LBMs (recycled clay bricks, fly ash cement, recycled steel, salvaged timber, compressed earth block (e.g. hydraform), sandbags, recycled polyester fibre, low emissivity glass, polystyrene blocks, eco-friendly paints), the challenges in their use and the extent of their use in the South African construction industry. Respondents were asked to 'indicate the degree of awareness of the indicators of environmental performance' and 'indicate the degree of impact of the indicators of challenges to the use of LBMs'. A five-point Likert scale was taken as the measurement scale.[56] The study constructs, the variables used in measuring the study constructs and their corresponding measurement scale are shown in Table 3.

**Table 3:** Study constructs and measurement scale

| | Constructs | Measurement scale |
|---|---|---|
| **Environmental performance** | Low embodied emissions | Respondents were asked to indicate their degree of awareness of the indicators of environmental performance on a five-point Likert scale of 1–5 where: 1 = not at all; 2 = barely aware; 3 = neutral; 4 = somewhat aware; 5 = very aware |
| | Low embodied energy | |
| | Low embodied cost | |
| **Challenges in the use of LBMs** | Technical challenges | Respondents were asked to indicate the degree of impact of the indicators of challenges in the use of LBMs on a five-point Likert scale of 1–5 where: 1 = not at all; 2 = barely aware; 3 = neutral; 4 = somewhat aware; 5 = very aware |
| | Environmental challenges | |
| | Policy challenges | |
| | Cultural challenges | |
| | Economic challenges | |
| **The extent of use of LBMs** | The present use of LBMs in projects | |
| | Future use of LBMs in projects | |

*LBMs, local building materials*

The constructs and sub-constructs were assessed for discriminant validity, reliability, internal consistency, convergent validity, and divergent validity. Convergent validity represents the extent of agreement between two or more variables of the same construct, and it was tested using the average variance. Convergent validity is established if the average variance explained is higher than 0.50. It indicates that the variables in the constructs explain at least half the variance of the constructs. Discriminant validity is established if there is a correlation between the constructs or sub-constructs.

The study population consisted of all the professionals and contractors in the South African construction industry. A total of 5920 email contacts of the registered professionals and contractors were identified from the Construction Industry Development Board (CIDB) database. This formed the target population for the study. Of the 5920 email contacts that were identified, 5% of the target population (296 email contacts) was taken as the sample size for the study. This followed the recommendations of Kotrlik and Higgins[57] for a large population. Thus 296 questionnaires were emailed to the respondents via the SurveyMonkey account of the Construction Business and Management Research Group, University of Cape Town, South Africa. At the end of the survey period, 232 valid responses were received, representing a response rate of 78.38%, and these responses were used for the data analysis. The data collected were analysed using descriptive and inferential statistical techniques. Structural equation modelling, a multivariate statistical analysis technique, was used to validate the causality between the constructs based on the estimate of maximum likelihood. Confirmatory factor analysis and path analysis were conducted to assess the validity of the constructs and sub-constructs. This technique has been widely used in built environment research (see, for example, Alaloul et al.[58]).

## Results

### *Profile of respondents*

Figures 2 and 3 present the demographic analysis of the 232 respondents. Figure 2 shows that the majority of the respondents have a Diploma with Grade 12 (34.1%) or a Higher National Diploma (21.1%). The findings on the designation of the respondents show that most are in the Management (18.1%) and Director (66.8%) professional group. Most of the respondents are construction managers (52.6%) and architects (32.3%). About 72% of the respondents work in the private sector, while 23.3% work in the public sector. The results indicate that LBMs are commonly used for residential (46.4%), institutional (20.3%), and commercial buildings (18.84%). Residential buildings constitute the highest percentage of all the buildings.

Figure 3 shows that the majority of the respondents, i.e. 49.1% and 12.9%, provide general contracting and sub-contracting services, respectively. Figure 3 also shows that 39.1% of the building projects identified by the respondents cost below ZAR1 million, while LBMs were also used on 18.8% of the projects that cost ZAR10 million to ZAR20 million. About 40% of the respondents indicated that they had made use of LBMs for projects sponsored by private clients. In comparison, 33.3% indicated that they had made use of LBMs for projects undertaken by provincial departments. Most of these projects (27.4%) were located in KwaZulu-Natal (KZN). Other significant locations for these projects were Gauteng (11.6%), the Western Cape (11.6%), the Free State (10.1%), and Limpopo (8.7%) Provinces of South Africa.

### *Extent and pattern of use of LBMs*

Figure 4 shows that eco-friendly paints (12.6%), sandbags (12.1%), and recycled steel (11.9%) are widely used as LBMs in South Africa. When distributed according to province, the results reveal that the prevailing LBMs used are: sandbags in the Free State; salvaged timber in the Northern Cape; recycled clay bricks, sandbags, and eco-friendly paints in Gauteng; and recycled clay bricks in the Eastern Cape. The results also reveal that recycled clay bricks are used in the Western Cape; recycled clay bricks in KZN and the North-West; sandbags in Limpopo; and recycled clay bricks, sandbags, and eco-friendly paints in Mpumalanga.

The use of LBMs was analysed according to climatic zones, using the Köppen–Geiger climate classification of subtropical, steppe, and arid climates, to group the provinces into climatic zones. Provinces such as the Western Cape, the Eastern Cape, and KZN fit into the subtropical climate classification. Provinces such as the Free State, Limpopo, Mpumalanga, and Gauteng were classified as having a steppe climate. In the classification, North-West and Northern Cape were considered to have an arid climate. As illustrated in Figure 4, recycled clay bricks were found to be the prevailing LBMs in the subtropical and arid climates, while sandbags were found to be commonly used in the steppe climate.

### *Modelling causality between availability, environmental performance, challenges and use*

#### Analysis of the measurement model

The results of the correlation between the constructs are presented in Table 4, while Figure 5 presents the results of the internal consistency test, Cronbach's alpha coefficient, and the average variance explained. The results show that the factor loading is above 0.50, which is acceptable; the Cronbach's alpha values for the constructs are more significant than 0.70, which indicates reliability. The average variance explained for the constructs is more significant than 0.50, which indicates convergent validity. These results indicate that the constructs and sub-constructs have acceptable validity and internal consistency, as shown by the average variance explained and Cronbach's alpha values, which were above the 0.50 and 0.70 thresholds, respectively.

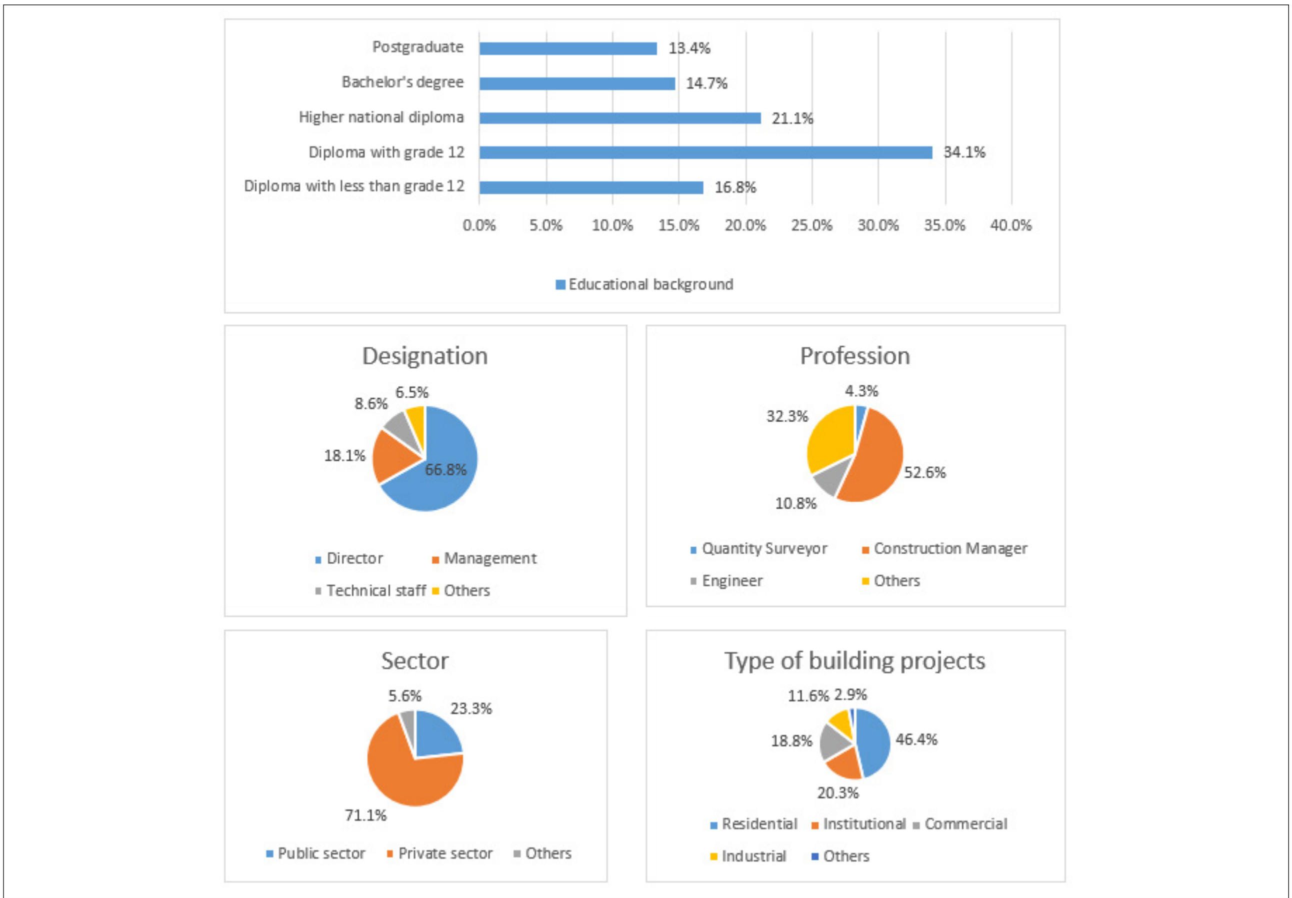



**Figure 2:** Personal profile of respondents.

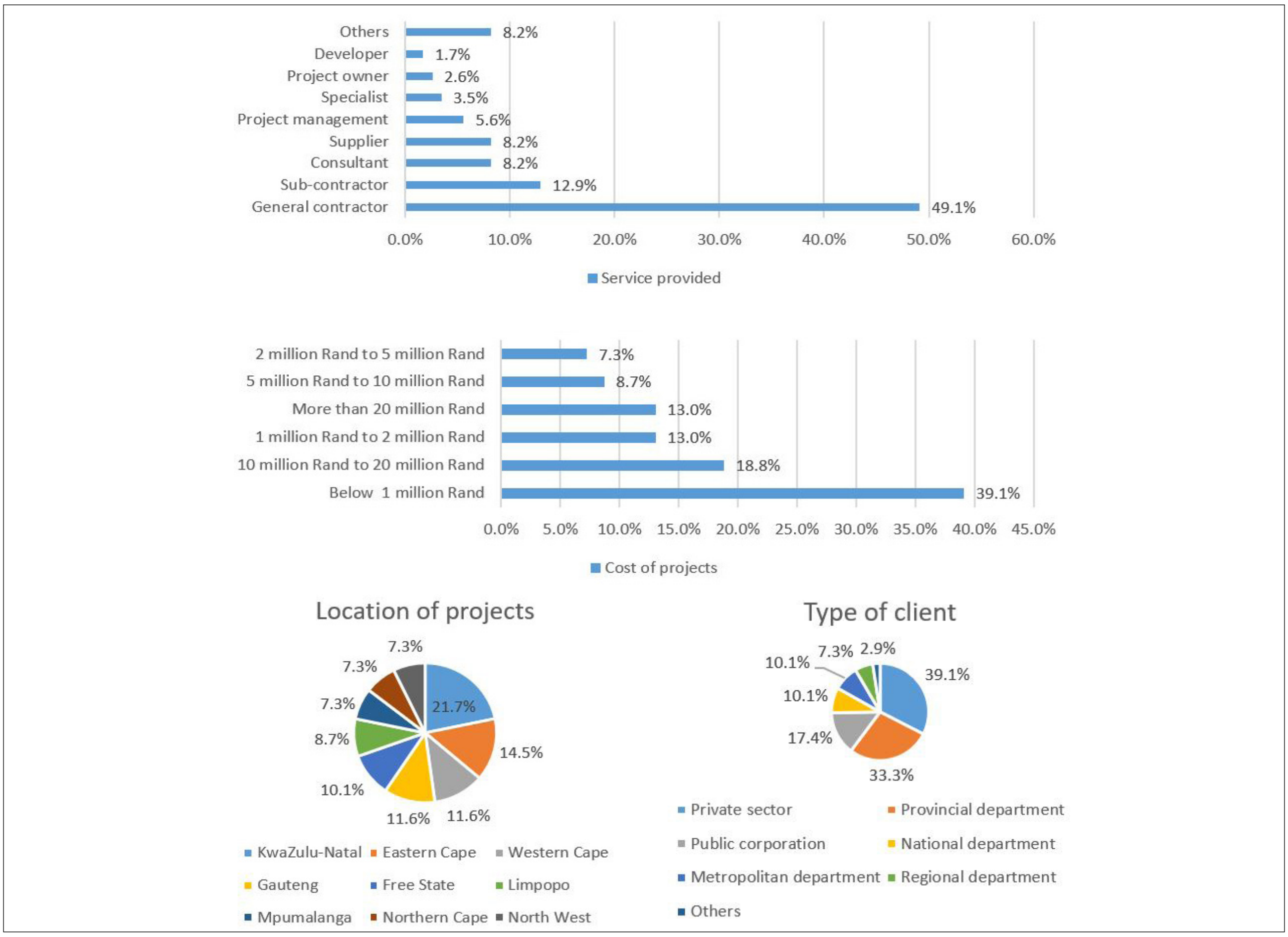
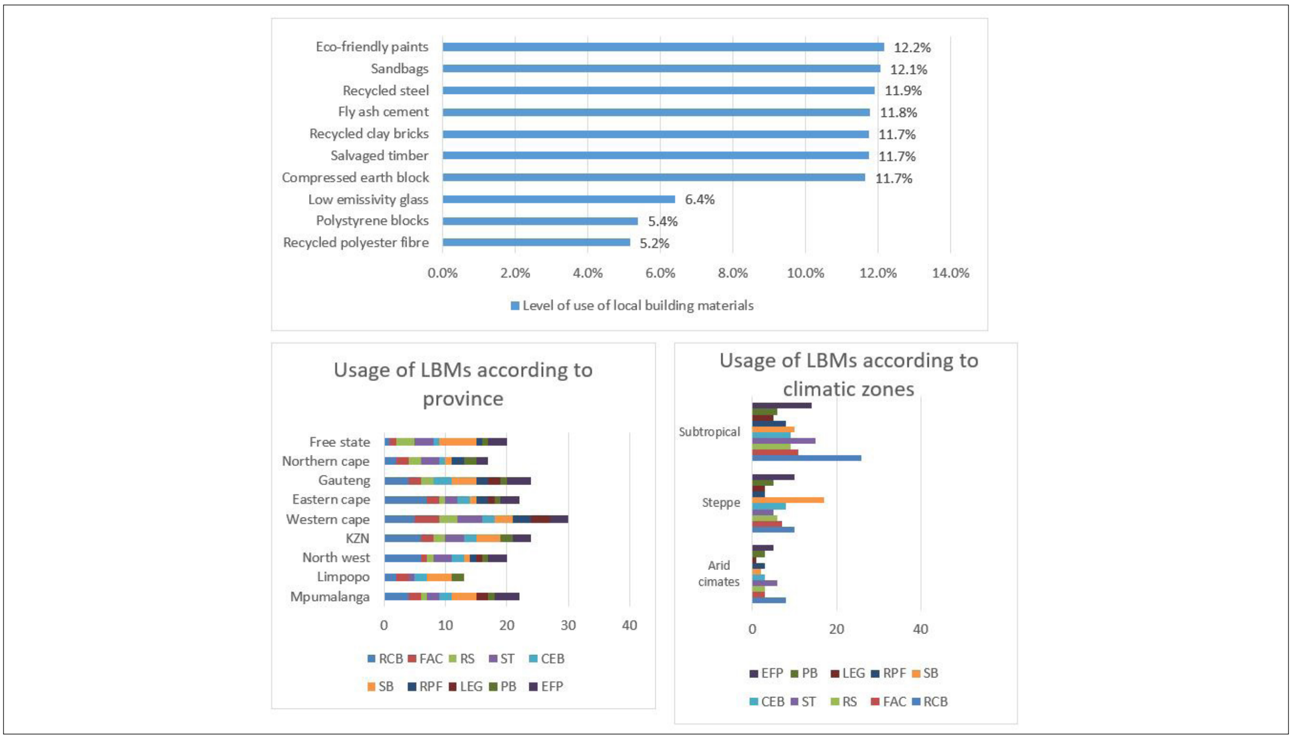



**Figure 3:** Professional profile of respondents.



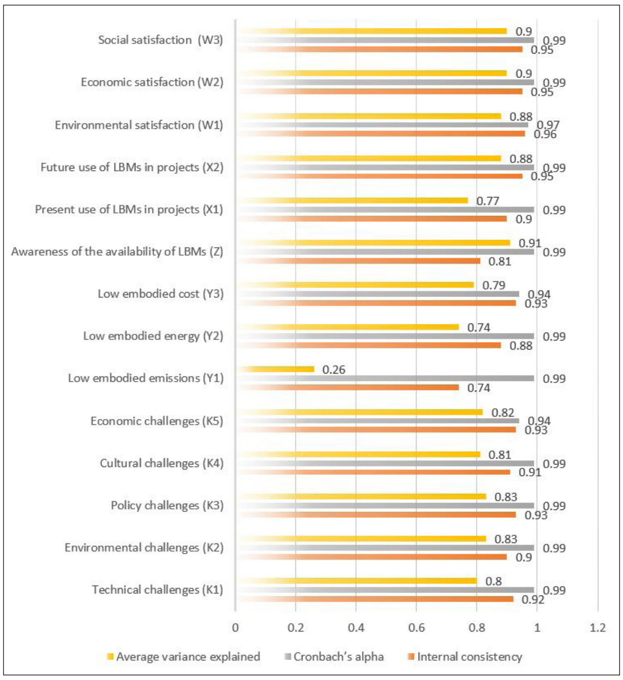

*RCB, recycled clay bricks; FAC, fly ash cement; RS, recycled steel; ST, salvaged timber; CEB, compressed earth block; SB, sandbags; RPF, recycled polyester fibre; LEG, low emissivity glass; PB, polystyrene blocks; EFP, eco-friendly paints*

*Note: arid climates – North-West, Northern Cape; steppe – Free State, Limpopo, Mpumalanga, Gauteng; subtropical – Western Cape, Eastern Cape, KwaZulu-Natal*

**Figure 4:** Level and pattern of use of local building materials.

**Table 4:** Discriminant validity analysis

| | K1 | K2 | K3 | K4 | K5 | Y1 | Y2 | Y3 | Z | X1 | X2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **K1** | 1 | | | | | | | | | | |
| **K2** | 0.356 | 1 | | | | | | | | | |
| **K3** | -0.061 | -0.500 | 1 | | | | | | | | |
| **K4** | 0.461 | -0.155 | 0.083 | 1 | | | | | | | |
| **K5** | 0.626 | 0.393 | 0.152 | 0.403 | 1 | | | | | | |
| **Y1** | 0.886 | 0.613 | -0.322 | 0.243 | 0.857 | 1 | | | | | |
| **Y2** | 0.590 | 0.337 | -0.167 | 0.538 | 0.574 | 0.766 | 1 | | | | |
| **Y3** | 0.561 | 0.236 | 0.068 | 0.511 | 0.473 | 0.508 | 0.881 | 1 | | | |
| **Z** | 0.293 | 0.348 | -0.068 | 0.064 | 0.052 | 0.784 | -0.268 | -0.297 | 1 | | |
| **X1** | 0.505 | -0.271 | 0.474 | 0.388 | 0.046 | -0.168 | 0.055 | 0.257 | 0.019 | 1 | |
| **X2** | -0.670 | -0.750 | 0.201 | -0.270 | -0.368 | -0.923 | -0.294 | -0.304 | -0.663 | -0.259 | 1 |




*LBMs, local building materials*

**Figure 5:** Internal consistency of the constructs and sub-constructs.

### Analysis of the structural model

Figure 6 illustrates the path analysis diagram for the structural model. It reveals 45 main constructs (*X, K, Y,* and *Z*) and 10 sub-constructs (*K1, K2, K3, K4, K5, Y1, Y2, Y3, X1,* and *X2*). Table 5 presents the results of the model estimation for the relationship between the main constructs and sub-constructs. As explained in Table 5, *K* has a negative but moderately significant correlation with *X* ($r$=-0.99, $z$=7.38) and *Y* ($r$=-7.02, $z$=55.39). Construct *Y* has a negative significant correlation with *K* ($r$=-7.02, $z$=55.39) and positive insignificant correlation with *X* ($r$=0.01, $z$=30.50). This result did not support H1. Construct *Z* has a positive but highly significant correlation with *X* ($r$=22.55, $z$=10.34) and *K* ($r$=3.79, $z$=38.69). Using the recommended value of 0.60 to determine the strength of the correlation and 0.50 to determine the significance of the correlation in the model, the results in Table 5 show that the parameter estimation for the items in the model is significant. This supports H2. Regarding the association between the constructs and sub-constructs, *K1, K2, K3, K4, X1, X2, Y1, Y2,* and *Y3* have between moderate and high correlation, and significance in the model. Table 5 presents the fit indices for the estimated model and shows that the fit indices are within the recommended values [chi square = 47572.086, RMSEA = 0.039, SRMR = 0.077, CFI = 0.979, TLI = 0.945]. These results (as shown in Table 5 and Figure 6) validate the causality between constructs *X, Y* and *Z* as theorised in H2. The causality between K, X, and Z, as proposed in H1, was not validated by the results shown in Table 5 and Figure 6.

## Discussion of findings

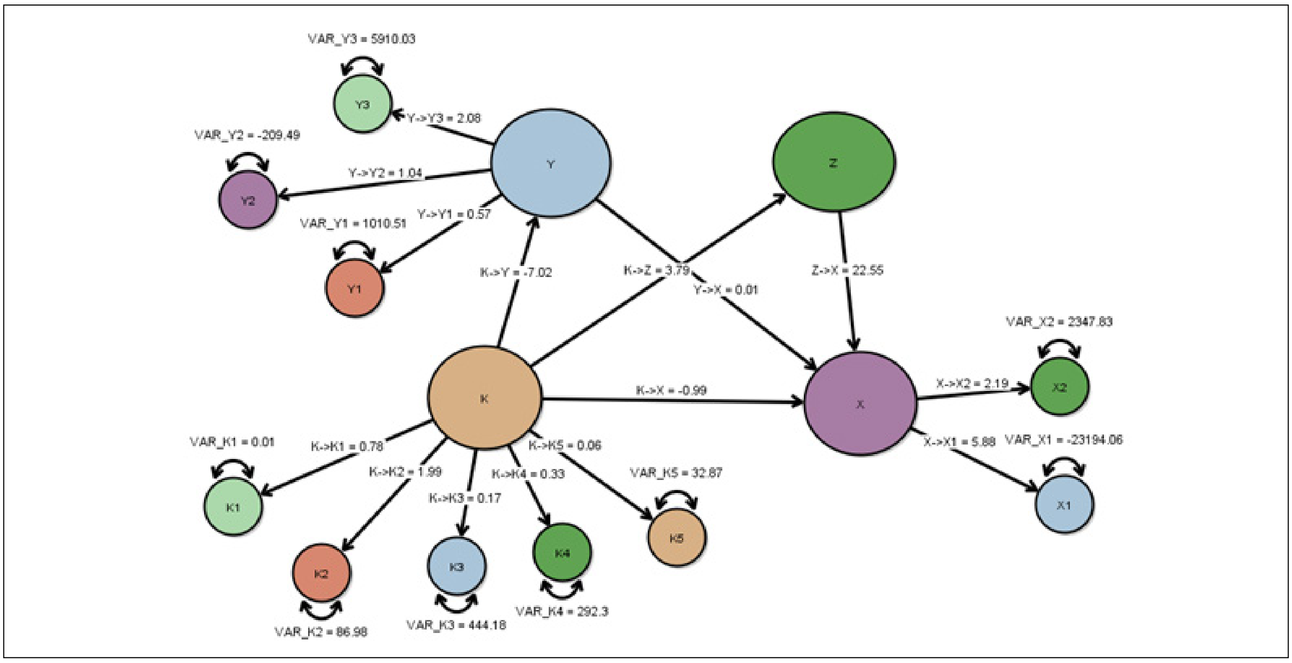
We tested the theory that the environmental performance of LBMs, which is their advantage, consisted of their demonstrated low embodied emissions, low embodied energy, and low embodied cost. These findings are aligned with the conclusions of previous studies by Darko and Chan[13], Mesthrige and Kwong[19], Bribián et al.[21], Mateus and Braganca[23] and Cabeza et al.[28] Specifically, Darko and Chan[13] concluded that awareness of the environmental friendliness of LBMs would promote their usage. Bribián et al.[21] deduced that LBMs have low embodied energy, which will encourage widespread usage; while Mateus and Braganca[23] maintained that the use of LBMs depends on the availability of information about their environmental friendliness.

Previous studies[11,17,18,20,47,49,51] have provided conclusions that are in line with the finding of a relationship between availability and reduced challenges in the adoption and use of LBMs. The findings by Darko et al.[17] and Nguyen et al.[18] established that there is a strong link between the availability of LBMs and the use of LBMs. Shen et al.[20] found that the awareness of the availability of LBMs through governmental policy will, in no small measure, influence the use of LBMs. Ahn et al.[15] concluded that the use of LBMs would promote environmental sustainability; while Mahmoudkelaye et al.[53] concluded that the decision to use LBMs is positively associated with the socio-cultural characteristics of the society in which the LBMs are to be used. Similarly, Mesthrige and Kwong[19] established that owners derive economic benefits from the use of LBMs because they significantly lower operating and maintenance costs.

The research established the existence of causality between the awareness of the availability of the LBMs, awareness of the environmental performance of the LBMs, and the extent of use of LBMs by construction stakeholders. These causal links, in turn, affect the existing challenges in the use of LBMs, as graphically described in Figure 1. The findings of the structural equation modelling prove the existence of causality between the awareness of the availability and environmental performance of the LBMs. These address the challenges to, and extent of use of LBMs by construction stakeholders. The hypotheses that were tested in this model explain that there is a relationship between challenges in the use of LBMs, the extent of awareness of their environmental performance, and the extent of their use by construction organisations (H1). The model also establishes the relationship between challenges in the use of LBMs, the extent of awareness of the availability of LBMs, and the extent of their

**Table 5:** Parameter estimation for the structural equation model of the awareness of the availability of local building materials (LBMs), awareness of the environmental performance of LBMs, challenges in the use of LBMs, and the extent of use of LBMs by construction organisations

| Relationships | Estimate | Standard error | *Z*-value |
|---|---|---|---|
| *K->K1* | 0.78 | 0.05 | 15.49 |
| *K->K2* | 1.99 | 0.02 | 71.56 |
| *K->K3* | 0.17 | 0.06 | 2.65 |
| *K->K4* | 0.33 | 0.05 | 6.01 |
| *K->K5* | 0.06 | 0.01 | 2.84 |
| *K->X* | -0.99 | 0.13 | 7.38 |
| *K->Y* | -7.02 | 0.12 | 55.39 |
| *K->Z* | 3.79 | 0.09 | 38.69 |
| *K1->X1* | 5.31 | 0.26 | 20.42 |
| *K1->X2* | 12.21 | 1.78 | 6.85 |
| *K1->Y* | 11.49 | 0.64 | 17.81 |
| *K1->Y1* | 5.78 | 0.81 | 7.10 |
| *K1->Y2* | 8.44 | 0.54 | 15.49 |
| *K1->Y3* | 37.07 | 1.07 | 34.36 |
| *K1->Z* | 2.00 | 0.12 | 15.49 |
| *K2->X1* | 26.58 | 0.48 | 54.46 |
| *K2->X2* | 12.99 | 1.13 | 11.46 |
| *K2->Y* | 13.89 | 3.54 | 3.92 |
| *K2->Y1* | 9.47 | 4.28 | 2.21 |
| *K2->Y2* | 7.99 | 0.86 | 9.24 |
| *K2->Y3* | 29.68 | 0.61 | 48.42 |
| *K2->Z* | 3.84 | 3.21 | 1.20 |
| *K3->X1* | 48.16 | 0.71 | 67.56 |
| *K3->X2* | 21.95 | 1.12 | 19.61 |
| *K3->Y* | 16.58 | 1.59 | 10.38 |
| *K3->Y1* | 61.50 | 3.01 | 20.38 |
| *K3->Y2* | 14.94 | 0.44 | 34.02 |
| *K3->Y3* | 26.41 | 0.86 | 30.59 |
| *K3->Z* | 8.45 | 0.24 | 35.07 |
| *K4->X1* | 38.25 | 0.47 | 80.15 |
| *K4->X2* | 22.81 | 1.33 | 17.09 |
| *K4->Y* | 17.22 | 1.04 | 16.44 |
| *K4->Y1* | 67.22 | 2.97 | 22.57 |
| *K4->Y2* | 15.94 | 0.43 | 36.82 |
| *K4->Y3* | 25.17 | 1.16 | 21.67 |
| *K4->Z* | 8.45 | 0.22 | 37.99 |
| *K5->X1* | 12.79 | 0.50 | 25.12 |
| *K5->X2* | 38.98 | 1.36 | 28.53 |
| *K5->Y* | 23.42 | 0.33 | 69.33 |
| *K5->Y1* | 17.01 | 0.19 | 86.14 |
| *K5->Y2* | 38.77 | 0.52 | 73.60 |
| *K5->Y3* | 50.25 | 0.52 | 97.87 |
| *K5->Z* | 21.66 | 1.79 | 12.06 |
| *X->X1* | 5.88 | 0.17 | 33.53 |
| *X->X2* | 2.19 | 0.03 | 61.11 |
| *Y->X* | 0.01 | 0.00 | 30.50 |
| *Y->Y1* | 0.57 | 0.03 | 14.60 |
| *Y->Y2* | 1.04 | 0.03 | 34.32 |
| *Y->Y3* | 2.08 | 0.06 | 30.70 |
| *Y1->X1* | 23.80 | 0.78 | 30.30 |
| *Y1->X2* | 87.64 | 2.01 | 43.60 |
| *Y2->X1* | 20.91 | 0.45 | 45.59 |
| *Y2->X2* | 18.28 | 0.39 | 46.76 |
| *Y3->X1* | 19.89 | 0.45 | 43.74 |
| *Y3->X2* | 29.63 | 2.32 | 12.79 |
| *Z->X* | 22.55 | 2.18 | 10.34 |
| *Z->X1* | 43.13 | 1.34 | 31.98 |
| *Z->X2* | 13.27 | 0.28 | 46.75 |




*Model chi-square: 47572.086; chi-square from independent: 9260.768; RMSEA: 0.039; SRMR: 0.077; CFI: 0.979; TLI: 0.945*

**Figure 6:** Path diagram for the structural equation model of the causality between the awareness of the availability and environmental performance of local building materials (LBMs), and the challenges in and extent of use of LBMs by construction stakeholders.

use by construction stakeholders (H2). As revealed in Figure 6, H1 was not validated.

The findings provide empirical evidence for the need to create awareness of the availability and environmental performance of LBMs, as well as the usefulness of awareness, in reducing the challenges in the use of LBMs and increasing their use in building projects. The non-validation of H1 suggests that the negative impacts of the challenges in the use of LBMs on the extent of their use will significantly reduce if there is an awareness of their environmental performance in the South African construction industry. This means that the awareness of the environmental performance of LBMs will convince the stakeholders in the construction industry of the advantages of using LBMs rather than conventional building materials.

Likewise, the validity of H2 indicates that the awareness of the availability of the LBMs will significantly increase the use of LBMs and indirectly reduce the challenges in the use of LBMs. The use of LBMs is advantageous as a result of their environmental friendliness; however, these advantages are not enough to promote their usage, unless they are readily available at building material stores, or from the building material suppliers.

## Conclusion

We investigated the extent and pattern of the use of LBMs in South Africa through two hypotheses (H1 and H2) testing the causality between availability and knowledge of the benefits of using LBMs, which were found to cause the extent of the low use of LBMs. The findings on the extent and pattern of use of LBMs revealed information about materials which are available and perform well in specific environments; for example, recycled clay bricks and sandbags were found to be the prevailing LBMs in subtropical, arid, and steppe climates. We conclude that climatic zones determine the choice and availability of LBMs in South Africa, which thus affects the extent of their use. The suitability of recycled clay bricks and sandbags to the climatic zones in South Africa confirms them as LBMs in this region.

We also conclude from the findings on causality between awareness of environmental performance, and use of LBMs (H1), that technical, environmental, policy, cultural, and economic challenges are limiting the use of LBMs on projects despite their positive environmental performance. The decision to use LBMs for building construction very much depends on the awareness of the availability and environmental performance of LBMs.

Based on the findings on challenges, awareness of availability, and use of LBMs (H2), we conclude that increasing awareness of environmental performance and availability of LBMs will bring about a reduction in the challenges in the use of LBMs. The results suggest that an increase in the use of LBMs for building projects will be caused by such awareness and that the negative influence of challenges in the use of LBMs on the extent of their use for building projects will be mitigated by awareness of the availability and environmental performance of LBMs. Based on these conclusions, there is a need for government agencies to alter their requirements and regulations in order to recognise the use of LBMs in building projects. These agencies should also investigate the technical properties of LBMs to establish whether they are suitable for use in construction. The conclusions also suggest the need to create awareness of the technical properties of LBMs through videos, seminars and workshops. Future studies should determine the properties of LBMs; scale up the use of LBMs; and test and standardise this technology for use in construction.

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## Data availability

The data contained in this paper are available in an open source repository (https://www.surveymonkey.com/results/SM-Vm1nXDEihk6TpMOUAxrxSg_3D_3D/), operated and maintained by the University of Cape Town.

## Competing interests

We have no competing interests to declare.

## Authors' contributions

A.W.: Lead author – made a substantial contribution to the conception of the research; acquisition, analysis and interpretation of the data; drafted the work and revised it critically for important intellectual content.

O.O.: Made a substantial contribution to the acquisition, analysis and interpretation of the data; drafted the work and revised it critically for important intellectual content. F.P.: Made a substantial contribution to the conception of the work; critically revised the work for important intellectual content. A.M.: Made a substantial contribution to the conception of the work and data acquisition. F.E.: A substantial contribution to writing and revising the work critically for important intellectual content.

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# The impact of wastewater treatment effluent on Crocodile River quality in Ehlanzeni District, Mpumalanga Province, South Africa

Excessive discharge of poorly treated effluent has impacted global water resource systems intensely. The declining state of wastewater treatment plants (WWTPs) is a significant source of pollution in water resources. There is evidence of water resource quality deterioration in natural environments caused by effluent discharges. We assessed the impact of wastewater treatment effluent on the quality of the Crocodile River. For spatial distribution, we collected data from three WWTPs discharging effluent into the Crocodile River and from three points situated downstream of each WWTP. Physicochemical and microbiological parameters such as pH, electrical conductivity, chemical oxygen demand, phosphates, nitrates, ammonia, and *Escherichia coli* were analysed using standard methods of the American Public Health Association. The water quality index was also calculated to give an overall indication of pollution within the catchment. The results show that WWTPs were not complying with the effluent standards set out in their water use licence. The WWTP effluent had a negative impact on downstream water quality, with the water quality index indicating low quality of discharged effluent. It is recommended that a regular and consistent water resource quality monitoring programme be implemented, particularly in areas where effluent discharges are prevalent.

**Significance:**

In many African nations, water pollution is a serious problem that may be traced to a variety of sources. Surface water pollution has adverse effects on aquatic ecosystems and reduces the availability of clean water. In most semi-arid to dry southern African regions (e.g. South Africa), water scarcity is a significant concern. In these regions, water is a vital resource that must be protected at all times, given that the inadequate infrastructure of wastewater treatment facilities adds to the decline in South Africa's water quality standards.

## Introduction

Water is essential for human survival and the long-term development of ecosystems.[1] Globally, population increase, urbanisation, industrialisation, and changes in consumption patterns have resulted in growing demands for freshwater resources.[2] The declining state of municipal wastewater treatment facilities and infrastructure is one of the largest contributors to pollution in water resources, especially surface water resources. Globally, around 80% of wastewater flows back into the environment as untreated or partially treated, which poses risks to downstream ecosystems and people who rely upon the river as a drinking water source.[3] Deterioration of the quality of a water resource, especially South African rivers, has a detrimental impact on socio-economic development because such water cannot be used for bathing, drinking, industry or agriculture. Surface water resources are more susceptible to pollution from various sources because surface water is most easily accessible for general uses.[4] Municipal wastewater treatment plants' effluent quality is an important factor in determining the best treatment technologies and impact on the ecology of receiving water bodies. Based on the influent wastewater and treated effluent information, the quality of recovered water sources for water reuse can also be evaluated.[5]

Industrial wastewater contamination is a significant issue in South Africa – a fast-growing country with limited freshwater resources. The country is currently designated as water-stressed[5,6] with just over 1200 $m^3$/person/year of fresh water available for a population of about 58.89 million people[7]. Effluents generated from both industrial and home activities are the second most common source of chemical and microbiological pollution of South Africa's water sources.[8] Previous research indicates that most municipal wastewater treatment plants (WWTPs) in South Africa rarely treat their wastewater to acceptable standards[8,9], while some engaged in the direct discharge of industrial effluents[10], thereby polluting receiving surface water sources. Furthermore, some WWTPs are ill-equipped to remove huge amounts of non-biodegradable trash and heavy metals[11], which are subsequently discharged into surface water sources[7]. Effective wastewater management will be required to ensure the long-term sustainability of key water supplies, particularly in urban areas. WWTPs are widely used around the world and are an important stage in improving the quality of wastewater before it is discharged into surface or groundwater and re-enters water systems. Many countries have worked to limit the volume of untreated wastewater discharges to rivers and streams during the last 50 years by closely monitoring and constantly improving municipal and industrial WWTPs.[12]

Although WWTPs are a desirable alternative to unregulated discharges, they do not discharge water of the same quality as that of the receiving water body and also cause physical changes to the receiving system. To avoid public health crises caused by contaminated water sources, efficient pathogen removal from wastewaters is required.[13] Conventional municipal wastewater treatment without appropriate tertiary treatment such as filtration or disinfection has been documented to pose a risk to public health from enteric pathogens, whether bacterial or otherwise.[12] Despite this, some enteric bacteria have been reported to be more resistant to the activated sludge and trickling filter treatment procedures.[14] Where effluent treatment is effective, the inactivation rates of enteric bacteria by chlorine treatment have been reported to be sufficient[15], but the absence of organic matter reduces the inactivation rates. Water quality monitoring, assessment and evaluation are important for pollution mitigation, control, and water resource management. Water quality monitoring is critical for identifying the major role players and contributors to spatial and temporal variations in quality, which can be beneficial concerning integrated water resource management.[16] Monitoring is important to ensure that the quality of water resources remains within acceptable limits for sustainable end-use.[17]

Given the abovementioned factors, in this study, we aimed to: (1) monitor the quality of the effluent in comparison with the resource quality objectives set for the catchment and/or with the water use licence, (2) determine the concentration of parameters such as ammonia, nitrates, phosphates, chemical oxygen demand, pH, conductivity, and bacteria, and (3) develop a comprehensive water quality index for the water resources sampling sites based on physicochemical and microbiological parameters associated with existing water resource quality standards.

## Materials and methods

### Study area

The Crocodile River catchment covers an area of about 10 500 km$^2$ and is located roughly 300 km east of Johannesburg in the Mpumalanga Province. It is the largest tributary of the Komati River, which it joins shortly before the border with Mozambique. The Lowveld area has developed rapidly and agricultural activities have greatly increased. These developments abstract large volumes of water from the river, resulting in a decline of the flow, especially during dry seasons. Extensive reeds dominate most of the river's riparian zone. The lowest reaches of the Crocodile River are considered to have poor water quality due to agricultural run-off as well as additional mining activities and poorly treated effluent from WWTPs. Figure 1 shows the study area map with sampling sites located within Mbombela and Nkomazi Local Municipalities, Mpumalanga Province. Ethical clearance to conduct the study was granted by Inkomati Usuthu Catchment Management Agency, and approved by the Cape Peninsula University of Technology's Higher Degree Committee.

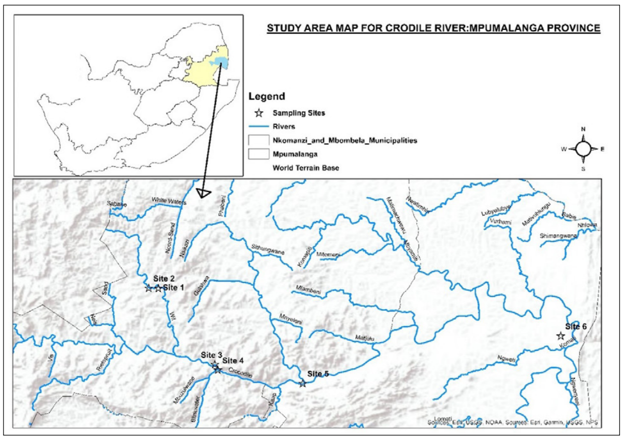


Figure 1: Map of the study area showing the location of sampling points.

### Sampling sites

Samples were collected from six sampling sites located in the study area within Mbombela Local Municipality and Nkomazi Local Municipality, which included three WWTPs discharging effluent into the Crocodile River. Within the river, a total of 108 samples were collected between 2017 and 2019. Table 1 lists the sampling sites and their coordinates.

### Physicochemical parameters

Wastewater samples used in determining the physicochemical and microbiological characteristics of effluent discharged and of the Crocodile River were collected from six sites between January 2017 and December 2019. Electrical conductivity and pH were determined in situ using a portable Hach Multimeter which was calibrated before use. A UV spectroscopy instrument was used to analyse ammonia, nitrite-nitrate, phosphate and chemical oxygen demand. Ammonia, nitrite-nitrate, phosphate, chemical oxygen demand, total suspended solids, and *Escherichia coli* were analysed at a laboratory accredited by the South African National Accreditation System as per the standard methods of the American Public Health Association.[18]

Table 1: Coordinates of the six sampling locations† across Crocodile River

| Sampling sites | Coordinates |
|---|---|
| White River wastewater treatment plant( Site 1) | S -25.31591; E31.04669 |
| White River – Crocodile River (Site 2) | S -25.31522; E31.02539 |
| Kanyamazane wastewater treatment plant (Site 3) | S -25.48649; E31.17166 |
| Kanyamazane N4 Bridge (Site 4) | S -25.49912; E31.17834 |
| Matsulu wastewater treatment plant (Site 5) | S -25.52907; E31.36631 |
| Downstream Komatipoort wastewater treatment plant (Site 6) | S -25.42271; E31.93726 |

*†The sampling points above were selected for the study based on the following factors: Site 1 is the main source of nutrient loading into the White River, which is one of the tributaries of Crocodile River, Site 2 is the point of confluence between White River and Crocodile River, Sites 3 and 5 discharge treated domestic effluent into the Crocodile River and Sites 4 and 6 are situated in a densely populated area with human activities taking place.*

### Water quality indices

The water quality index (WQI) was used to establish the quality of the water resource and its suitability for supporting aquatic life and social and economic development. The categorisation of water quality based on its quality index is shown in Table 2. Water quality parameters analysed for three different sampling sites (Site 2, Site 4 and Site 6) were used to calculate the WQI. These sites were used for the calculation of the WQI because they are located in the water resource and represent the overall quality of the river at that particular sampling point. The calculation of the WQI was conducted using a weighted arithmetic WQI which was originally proposed by Horton[19] and developed by Brown et al.[20] The weighted arithmetic WQI is shown by Equation 1:

$$WQI_A = \sum_{i=1}^{n} w_i q_i \,/\, \sum_{i=1}^{n} w_i, \qquad \text{Equation 1}$$

where $n$ is the number of variables or parameters, $w_i$ is the relative weight of the $i^{th}$ parameter and $q_i$ is the water quality rating of the $i^{th}$ parameter. The unit weight ($w_i$) of the various water quality parameters is inversely proportional to the recommended standards for the corresponding parameters. According to Brown et al.[20], the value $q_i$ is calculated using Equation 2:

$$q_i = 100\left[\frac{(V_i - V_{id})}{(S_i - V_{id})}\right], \qquad \text{Equation 2}$$

where $V_i$ is the observed value of the $i^{th}$ parameter and $V_{id}$ is the ideal value of the $i^{th}$ parameter in the resource quality objectives. All the ideal values ($V_{id}$) are zero except for pH.[21] For pH, the ideal value is 7.0 (for natural water ) and the permissible value is 8.5 for polluted water. Therefore, the quality rating for pH is calculated from Equation 3:

$$q_{pH} = 100\left[\frac{(V_{pH} - 7.0)}{(8.5 - 7.0)}\right], \qquad \text{Equation 3}$$

where $V_{pH}$ is the observed value for pH.

Table 2: Water quality classification based on the weighted arithmetic water quality index[20,22]

| Water quality index | Water quality status / classification |
|---|---|
| **0–25** | Class 1 – Good water quality |
| **26–50** | Class 2 – Acceptable water quality |
| **51–75** | Class 3 – Regular water quality |
| **76–100** | Class 4 – Poor water quality |
| **>100** | Class 5 – Very poor water quality |

## Results and discussion

The heat maps allowed us to explore large data sets and visualise important cases or clusters. Figure 2 depicts changes in water quality indicators analysed per sample location from 2017 to 2019 over two separate seasons (dry and wet). For each parameter studied, data were categorised and compared based on time and season. The actual numerical values are shown in the supplementary material. Water quality data were compared by season (dry and wet) because rainfall run-off has a major influence on the quality of a water resource and the quality of discharged effluent, as well as acting as a diluting factor on the overall concentration of waste.[23]

The water body receiving treated effluent from wastewater treatment around the White River WWTP (Site 1) had a wide range of pathogenic microorganisms. In particular, the region got a significant amount of ammonia ($NH_3$) in 2017 when compared to the other locations (Sites 3 and 5) in the same year. The levels of ammonia were above the legal limit which is set for White River WWTP as per the effluent discharge quality limits for the WWTP water use licence within that area (Table 3). High levels of nitrate ($NO_3$) and nitrite ($NO_2$) were observed from Site 1 in the 2019 wet season. WWTP effluent had a considerable impact on ammonium and nitrate concentrations in the water which means that a post-treatment may be required for removal of nitrate,

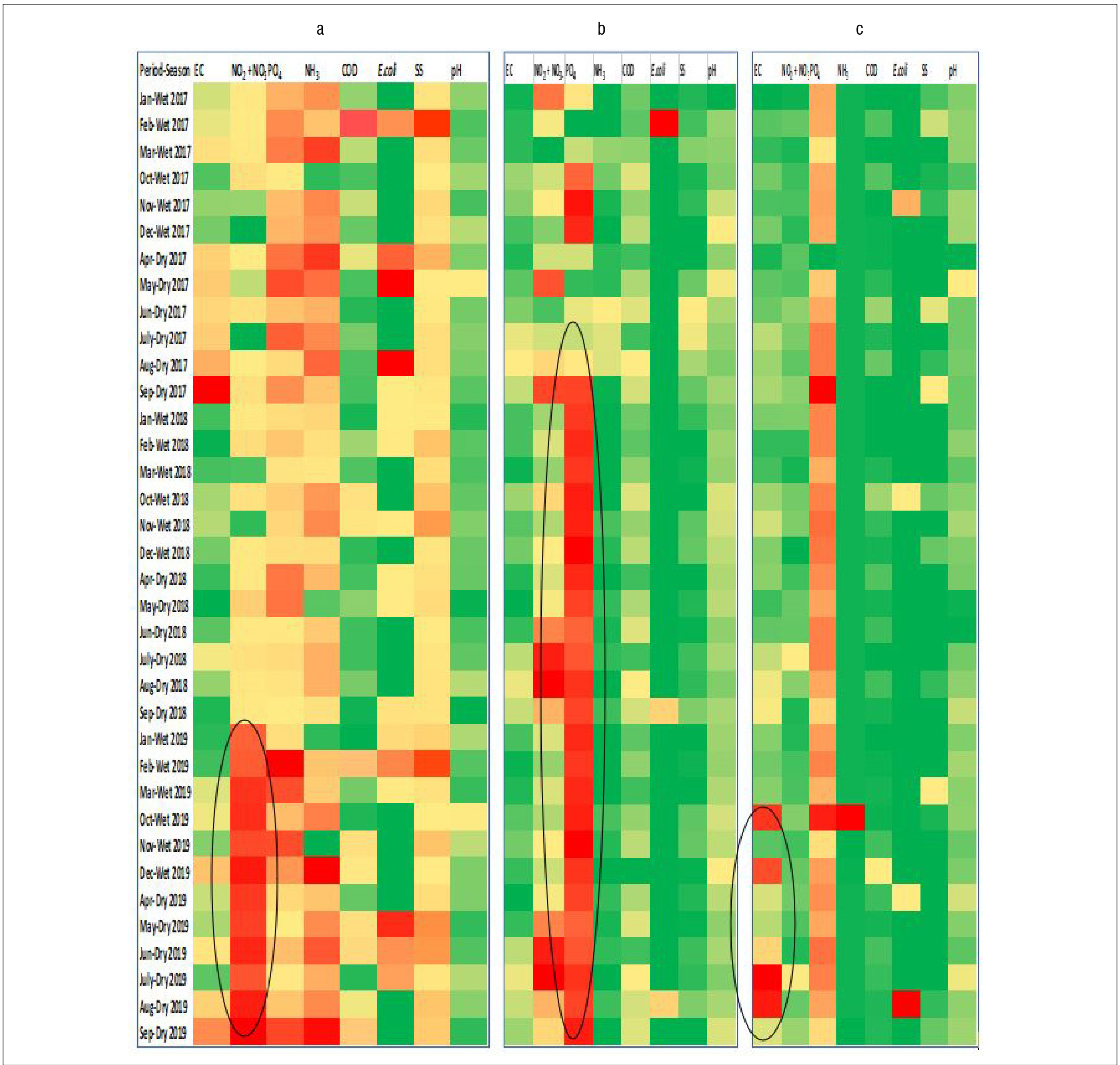


**Figure 2:** Heat maps showing variations in water quality parameters for (a) White River wastewater treatment plant (WWTP) Site 1, (b) Khanyamazane WWTP Site 3 and (c) Matsulu WWTP Site 5. The higher the intensity of the red colour, the higher the measured parameter. The higher the intensity of the green colour, the lower the measured parameter.

**Table 3:** Effluent discharge quality limits as per White River wastewater treatment plant (WWTP) water use licence

| | pH | Electrical conductivity | $NO_2 + NO_3$ | *E. coli* | Suspended solids | $PO_4$ | $NH_3$ | Chemical oxygen demand |
|---|---|---|---|---|---|---|---|---|
| **White River WWTP** | 5.5–9.5 | 70 | 15 | 0 | 25 | 1 | 1 | 75 |
| **Khanyamazane WWTP** | 5.5–9.5 | 75 | 15 | 0 | 25 | 1 | 6 | 75 |
| **Matsulu WWTP** | 5.5–9.5 | 70 | 15 | 0 | 25 | 1 | 3 | 75 |

residual ammonia, and nitrite, depending on the type of procedure used to conduct the anammox conversions and the effluent requirements. Nitrate in waste effluents can come from a variety of sources, including home and agricultural wastes, as well as N-containing fertilisers. Ammonium nitrogen (which is abundant in raw waste) is completely or partially oxidised to nitrate by microbial action, resulting in high nitrate concentrations in treated wastewater. In locations with strong population pressure and agricultural expansion, nitrate pollution of raw drinking water is common. The results above are in line with other studies which were conducted in South African rivers such as the Mhlathuze River, Vaal River and Klip River.[24,25]

Site 3 had a high level of phosphate from 2017 to 2019; levels were above the required limits as outlined in the water use licence (Table 3). Phosphate concentration was frequently outside the set limit as evidenced in the water quality data during the wet season from 2017 to 2019, with a lower mean concentration in 2017 compared to the same periods in 2018 and 2019. Phosphorus removal in activated sludge systems such as WWTPs (Site 3) relies mainly on phosphorus accumulating organisms for enhanced biological phosphorus removal. Bunce et al.[5] outline that operating conditions, including prerequisites for metabolism such as carbon, glycogen and electron acceptor requirements, are very important for the growth of such organisms, hence the adjustment of such factors must be undertaken to promote the proliferation of phosphorus accumulating organisms and ultimately remove phosphorus from wastewater. The results from the study conducted by Bunce et al.[5] show that the plant does enable phosphorus present in wastewater; however, the system is unable to produce an effluent with a phosphate concentration of less than 1 mg/L as per the water use licence limit. The results are in line with a study conducted by Cai et al.[26] which revealed that biological nutrient removal systems do not completely remove phosphorus present in wastewater, but remove only around 60% of the total influent phosphorus.

Site 5 (Matsulu WWTP) was located downstream of Site 4. This WWTP treats domestic wastewater from Matsulu township and discharges effluent into the Crocodile River. The plant is situated in a residential area that is also dominated by agricultural land-use activities. Although one would have expected high levels of phosphate, nitrate and ammonia (as for Site 1), Site 5 had relatively low rates of these parameters, which shows that there are anthropogenic activities taking place around the area or sewage. Although there were some spikes of *E. coli* around August 2019, low levels of *E. coli* were found throughout the sampling times (2017 to 2018). The same trend can be observed for the phosphate levels from 2017 to 2019. Site 5 had a high rate of electrical conductivity around the 2019 dry season, which was above the effluent quality limits as per Matsulu WWTP's water use licence (Table 3). Other studies have found that, during months of low precipitation such as winter in South Africa, significantly higher electrical conductivity and salinity occur, because enhanced evaporation results in a more concentrated effluent.[27,28] Water's electrical conductivity is a quick and straightforward way to determine its salinity or total salt content. Domestic sewage effluents can contain high levels of dissolved salts. High salt concentrations in waste effluents can raise the salinity of receiving water, which can have negative ecological consequences for aquatic life. As a result, when combined with other parameters and when the source of dissolved salts is not of natural geological origin, electrical conductivity can be a good salinity indicator.

### *Physicochemical parameters*

Table 4 shows the standard set by the South African Department of Water Affairs as per the Government Gazette no. 39614 issued on 22 January 2016 and issued water use licences. Crocodile River is generally classified as Class C in regard to ecological status, that is, intended to support farming, commercial and sustenance fishing.

Figure 3 shows heat maps depicting changes in water quality parameters analysed per sampling site (Sites 2, 4 and 6) in the Crocodile River. Water quality data were compared according to seasons (dry and wet) because rainfall run-off has a significant impact on the quality of a water resource. For each parameter studied, data were categorised and compared based on time and season. Two parameters – namely chemical oxygen demand and suspended solids – which were analysed on samples from the effluent of the WWTP were not analysed in samples taken from these sites because they are situated within the water resource (river) and there is no set limit for such parameters on the resource quality objectives.

**Table 4:** Resource quality objectives set for the Crocodile River water[29]

| Constituents | Limits |
|---|---|
| Electrical conductivity (ms/m) | 70 |
| Nitrite and nitrates (mg/L) | 6 |
| Phosphate (mg/L) | 0.125 |
| Ammonia-N (mg/L) | 6 |
| *E. coli* (count per mL) | 130 |
| pH | 6.5–8.5 |

Figure 3 shows heat maps for Site 2, Site 4 and Site 6 analysed for visualisations of the results obtained in the Crocodile River. Parameters from all three sites were compared to the standard set by the Department of Water Affairs as per Government Gazette no. 39614 and issued water use licences to check if they complied with the set standards. Site 1 is a confluent point between White River and Crocodile River, and the area is mostly dominated by agricultural land-use activities. Data revealed that water resource quality at this site was compliant with the set limits for parameters outlined in the resource quality objectives in most months (Table 4). Although Site 2 was compliant with the set limits, in the 2017 wet season, it recorded values above the legal limits. The site is situated downstream of the White River WWTP, and so it was expected that, as the effluent from the WWTP had high *E. coli* counts during 2017 and 2019 of the same periods, this site would exhibit higher *E. coli* counts during these months; however, higher *E. coli* counts were noted in 2017 only. It was also noted that the area received minimal rainfall of between 100 mm and 200 mm between April and May 2019. These results contradict those of Abia et al.[30] who outlined that run-off from the storm influenced the concentration of *E. coli* in the water resource because run-off carries sediments containing microorganisms into the river.

The Kanyamazane N4 Bridge (Site 4) is located downstream of Kanyamazane WWTP (Site 3) which is densely populated, and water resource quality is mostly influenced by anthropogenic activities undertaken within the surrounding informal settlements. In 2017, Site 4 recorded high levels of *E. coli* when compared to those in 2018 and 2019. The recorded levels of *E. coli* were above the standard set by the Department of Water Affairs as per Government Gazette no. 39614 and issued water use licences (Table 4). The overall status of the quality of the water resource reveals that it is not compliant with the set limit. A similar trend was also observed from Site 2, whereby higher *E. coli* counts were observed during the 2017 and 2018 periods and lower counts were noted in samples collected in 2019. This sampling site is situated in a densely populated area in the township called Kanyamazane; the site is also situated approximately 300 m downstream of Kanyamazane WWTP discharge point. The results are in line with the study conducted by Amoah et al.31 who outlined that, in addition to the treated effluent discharged into the river, informal settlements situated near the water resources had an impact on the microbial quality of the water resources, as indicated mostly by the presence of *E. coli*. The downstream chemistry and bacterial populations of these rivers were considerably affected by WWTP wastewater. Inorganic nitrogen and phosphorus concentrations were higher downstream of the effluent, similarly to that seen in several habitats.

Site 6 is located approximately 50 m downstream of Komatipoort WWTP, which primarily treats domestic wastewater from Komatipoort Town. The area is mostly dominated by agricultural land-use activities (sugar cane, maize). The overall status of the quality of the water resource reveals that it is not compliant with the set limit (Table 4). This sampling site is also situated in a populated area in the town of Komatipoort and is approximately 200 m downstream of Komatipoort WWTP discharge

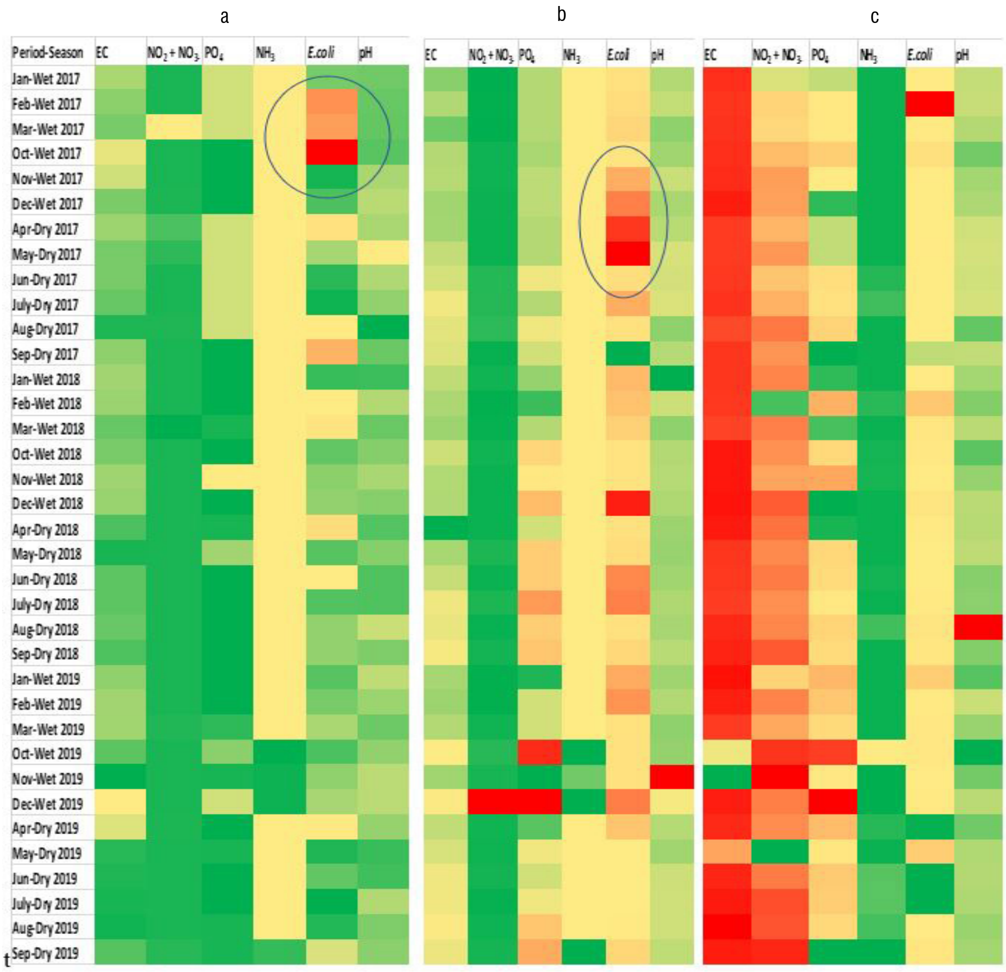


**Figure 3:** Heat maps showing variations in water quality parameters for (a) White River – Crocodile River (Site 2), (b) Kanyamazane N4 Bridge (Site 4) and (c) downstream Komatipoort wastewater treatment plant (Site 6). The higher the intensity of the red colour, the higher the measured parameter. The higher the intensity of the green colour, the lower the measured parameter.

point. Site 6 recorded high levels of electrical conductivity, irrespective of year or season, which were above the required levels as set by the Department of Water Affairs as per Government Gazette no. 39614 and issued water use licences (Table 4). This limit was exceeded in river water samples, and the parameter is alarming, while the effluent discharge has remained consistent when looking at the WWTP (Site 5). But electrical conductivity in the river was higher (relative to measurements at the reference location), indicating a significant impact. Within the same site, levels of nitrate and nitrite were high during the years 2018 and 2019, rendering the river non-compliant with the set limits (Table 4). Site 6 showed a trend distinct from those of Sites 2 and 4 as it recorded high electrical conductivity, nitrate and nitrite, irrespective of the season during which the samples were collected. Because of the presence of chloride and phosphate, a failed sewage system would increase conductivity. But because the Crocodile River is classified as Class C ecological status, intended to support farming, commercial and sustenance fishing, the concentration of nitrates in river water is not thought to be a hazard for residential usage. However, eutrophication makes nitrate an issue for other applications. Therefore, non-point sources are said to account for almost two thirds of contaminant loading in surface waterways, with nitrate being the most common pollutant. Excess $NO_3$ and $NO_2$ can cause eutrophication – a growing concern in many developing countries.

## *Water quality Index*

Classification of the water quality of the water resource relating to the weighted arithmetic WQI is shown in Table 2 and the computed WQI for different sites (Sites 2, 4, 6) is shown in Tables 5–7. The present index is based on the desirable and permissible limits of *E. coli,* pH, electrical conductivity, phosphate, nitrite-nitrate and ammonia as defined by the resource quality objectives of Crocodile River.

### White River – Crocodile River confluence (Site 2)

Table 5 shows the calculation of the WQI of Crocodile River at Site 2 and the standard values of the selected six water quality parameters according to the resource quality objective of the catchment (see Table 2). Based on the classification of the water quality concerning the weighted arithmetic WQI method as shown in Table 4, the WQI for Site 2 was 31.27, which indicates acceptable water quality. These results are in line with a study conducted by Şener et al.[32] to evaluate the water quality of Aksu River using a WQI. The study included 21 sampling sites located within the river and it was observed that the WQI of sampling sites located mostly in the middle region ranged between 37.6 and 62.9 during both dry and wet seasons, showing water of good quality.

### Kanyamazane N4 bridge (Site 4)

Table 5 shows the calculation of the WQI of Crocodile River at Site 2. Based on the classification of the water quality shown in Table 6, the WQI value of Site 4 was 101.18, which indicates very poor water quality. It can be observed that the poor water quality can be attributed to high *E coli* counts present in the water. These results are in line with the study conducted by Ewaid et al.[33] who outlined that WQI values showing

**Table 5:** Calculation of the water quality index (WQI) of the Crocodile River at Site 2

| Parameter | Standard value (Sn) | 1/Sn | ∑1/Sn | K=1/(∑1/Sn) | Wi=K/Sn | Ideal value (Vo) | Mean conc. value (Vn) | Vn/Sn | Qn=Vn/Sn*100 | WnQn |
|---|---|---|---|---|---|---|---|---|---|---|
| *E. coli* | 130 | 0.0076 | 8.472 | 0.1180 | 0.0009 | 0 | 314.03 | 2.415 | 241.56 | 0.2193 |
| pH | 8.5 | 0.1176 | 8.472 | 0.1180 | 0.0138 | 7 | 7.64 | 0.42 | 42 | 0.5831 |
| Electrical conductivity | 70 | 0.0142 | 8.472 | 0.1180 | 0.0016 | 0 | 30.83 | 0.440 | 44.04 | 0.0742 |
| Phosphates | 0.125 | 8 | 8.472 | 0.1180 | 0.9441 | 0 | 0.0401 | 0.3208 | 32.08 | 30.289 |
| Nitrate + nitrite | 6 | 0.1666 | 8.472 | 0.1180 | 0.0196 | 0 | 0.1331 | 0.0221 | 2.218 | 0.0436 |
| Ammonia | 6 | 0.1666 | 8.472 | 0.1180 | 0.0196 | 0 | 0.1803 | 0.0300 | 3.005 | 0.0591 |
| Sum (∑) | | | | | 1 | | | | | WQI=31.27 |

**Table 6:** Calculation of the water quality index (WQI) of the Crocodile River at Site 4

| Parameter | Standard value (Sn) | 1/Sn | ∑1/Sn | K=1/(∑1/Sn) | Wi=K/Sn | Ideal value (Vo) | Mean conc. value (Vn) | Vn/Sn | Qn=Vn/Sn*100 | WnQn |
|---|---|---|---|---|---|---|---|---|---|---|
| *E. coli* | 130 | 0.0076 | 8.472 | 0.1180 | 0.00090 | 0 | 2404 | 18.49 | 1849.23 | 1.68 |
| pH | 8.5 | 0.1176 | 8.472 | 0.1180 | 0.01389 | 7 | 7.82 | 0.53 | 53 | 0.74 |
| Electrical conductivity | 70 | 0.0142 | 8.472 | 0.1180 | 0.00169 | 0 | 25.48 | 0.364 | 36.4 | 0.061 |
| Phosphates | 0.125 | 8 | 8.472 | 0.1180 | 0.94418 | 0 | 0.13 | 1.04 | 104 | 98.19 |
| Nitrate + nitrite | 6 | 0.1666 | 8.472 | 0.1180 | 0.01967 | 0 | 1.38 | 0.23 | 23 | 0.452 |
| Ammonia | 6 | 0.1666 | 8.472 | 0.1180 | 0.01967 | 0 | 0.18 | 0.03 | 3 | 0.059 |
| Sum (∑) | | | | | 1 | | | | | WQI=101.18 |

**Table 7:** Calculation of the water quality index (WQI) of the Crocodile River at Site 6

| Parameter | Standard value (Sn) | 1/Sn | ∑1/Sn | K=1/(∑1/Sn) | Wi=K/Sn | Ideal value (Vo) | Mean conc. value (Vn) | Vn/Sn | Qn=Vn/Sn*100 | Wn Qn |
|---|---|---|---|---|---|---|---|---|---|---|
| *E. coli* | 130 | 0.0077 | 8.472 | 0.1180 | 0.00091 | 0 | 2144 | 16.49 | 1649.23 | 1.50 |
| pH | 8.5 | 0.1176 | 8.472 | 0.1180 | 0.01388 | 7 | 8.1 | 0.73 | 73 | 1.013 |
| Electrical conductivity | 70 | 0.0142 | 8.472 | 0.1180 | 0.00168 | 0 | 125.3 | 1.79 | 179 | 0.301 |
| Phosphates | 0.125 | 8 | 8.472 | 0.1180 | 0.94418 | 0 | 0.67 | 5.36 | 536 | 506.08 |
| Nitrate + nitrite | 6 | 0.1667 | 8.472 | 0.1180 | 0.01967 | 0 | 9.14 | 1.52 | 152.3 | 2.99 |
| Ammonia | 6 | 0.1667 | 8.472 | 0.1180 | 0.01967 | 0 | 0.488 | 0.081 | 8.13 | 0.160 |
| Sum (∑) | | | | | 1 | | | | | WQI=512.05 |

poor water quality as observed from Site 3 can be attributed to natural phenomena and anthropogenic activities such as wastewater discharge occurring along the river. Medeiros et al.[34] also conducted a similar study on the quality index of surface water of Amazonian rivers and noted that WQIs determined for the water resources flowing through or located near urban centres or populated areas were impacted by domestic and industrial untreated effluents; they highlighted that lack of adequate sanitation services and treatment processes has been the main reason for water quality deterioration in these water resources.

### Downstream Komatipoort WWTP (Site 6)

Table 7 shows the calculation of the WQI of Crocodile River at Site 6. The WQI of Site 6 was 512.05. Based on the classification of the water quality (Table 2), it was observed that the quality of the water was very poor. This site is situated approximately 50 m downstream of Komatipoort WWTP . These results are also in line with a study conducted by Şener et al.[32] who evaluated the water quality of Aksu River using a WQI and observed that the WQI value for certain sampling sites located in the upper regions of Aksu River reached a maximum of 304.51 during the dry season and 304.33 during the wet season, which indicates extremely poor water quality. From tributaries data, they outlined that the reason for such poor water quality was the input of municipal and industrial wastewater discharged at the banks of the river[32], which also supports the high effluent noted at Site 5.

## Conclusion and future research

The assessment of the impact of wastewater treatment effluent on water quality of the Crocodile River based on the physicochemical and microbiological parameters and indices indicates the quality of the water resources is impacted due to poorly treated discharged effluent, evidenced by higher WQIs of 101.18 and 512.05 observed at Site 4 and Site 6, respectively, which is mostly attributed to high *E. coli* counts frequently recorded during the study. These results obtained in the current study suggest there is a WWTP effluent related pollution in the Crocodile

River. Based on the results of our study, the pollution of the Crocodile River can be attributed to, amongst other non-point sources, poor quality effluent discharged into the water resource. Poorly treated effluent from WWTPs discharged into the water resources has a significant impact on the functioning, integrity, and quality of the water resource and associated ecosystem. Several studies were also conducted on the impact of wastewater effluent on the receiving environment and they confirm that there is still a lot of work that needs to be undertaken in regard to improving effluent quality to protect our water resources.

## Recommendations

- A call to vigilance and aggression by responsible authorities with regard to compliance monitoring and enforcement of effluent discharge laws and regulations to ensure minimal pollution in rivers and streams.
- A comprehensive and detailed study including all WWTPs located within the Crocodile River catchment, covering a wide period of water quality data (15 to 20 years ) should be undertaken to successfully assess the overall impact.
- A public awareness and education programme, especially in densely populated areas situated next to a water resource, is needed to educate the public on the importance of water resources and measures that can be taken by settlers to reduce non-source pollution.
- A scheduled continuous operations and maintenance programme for wastewater treatment works and related infrastructure must be put in place to ensure effective operation.
- The local government should conduct a feasibility study, and assess and invest in post-treatment technologies that can be integrated into current process technology to enhance the operation and ensure compliance of discharged effluent with set standards.

## Acknowledgements

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## Data availability

Raw data from Inkomati Usuthu Catchment Management Agency (IUCMA) were used in the study. The information can be requested from IUCMA https://www.iucma.co.za

## Competing interests

We have no competing interests to declare.

## Authors' contributions

T.T.P. conducted the study and the collection of data was relevant for the writing of the article. All authors contributed to conceptualisation, structuring and writing the article.

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# Nitrogen isotopes of *Eichhornia crassipes* (water hyacinth) confirm sewage as leading source of pollution in Hartbeespoort Reservoir, South Africa

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Nitrogen (N) isotopes of aquatic organisms offer a way of differentiating sources of dissolved nitrate species in water. Water quality in the Hartbeespoort Reservoir has been a problem for many decades, causing excessive growth of algae and water hyacinth, both of which further cause human health issues, degradation of environmental water quality, and recreational hazards. Six boreholes and four surface water locations were sampled and analysed for certain water quality parameters and stable water isotopes (H and O). Electrical conductivity and pH were acceptable, but faecal coliforms and *Escherichia coli* were high in the Crocodile River. δD and $\delta^{18}O$ showed that there is little groundwater input to the reservoir and the surface water experiences significant evaporation. Six samples of water hyacinth were analysed for C and N stable isotopes. The $\delta^{15}N$ values ranged from 20‰ to 33‰, indicating sewage or manure as the primary source of dissolved N in Hartbeespoort Reservoir. As high dissolved N concentrations cause water hyacinth growth to outstrip any manual, chemical or biological control measures, it is suggested that efforts to control the water hyacinth infestation on Hartbeespoort Reservoir focus on informal settlement sanitation and upgrades to sewage treatment works in the Crocodile River catchment.

**Significance:**

This work is possibly the first report on nitrogen isotopes in plant material to trace water pollution in South Africa. It presents a new line of evidence regarding eutrophication in the Hartbeespoort Reservoir. It indicates the optimal management method for controlling water hyacinth on this and other waterbodies. The study has relevance for agriculture, urban wastewater management, informal settlement sanitation, invasive alien plant control, recreation and tourism.

## Introduction

Declining water quality due to human activities is a global trend of increasing concern.[1] This phenomenon has been known for decades[2,3] and awareness to address the issue has extended into the less industrialised parts of the world, including Africa[4-6]. One of the key pollutants in surface, groundwater and coastal water across the world is nitrogen (N), in the form of various dissolved species, such as nitrate, nitrite and ammonium.[7-9] Nitrate is the dominant form in environmentally active waters, as it is the most oxidised species. Sources of nitrate in water include sewage (human faeces), manure (animal faeces), compost (plant wastes), inorganic fertiliser (N-P-K type fertilisers), N-based explosives and natural nitrogen-fixing bacteria in plant roots.

Nitrogen has two stable isotopes: $^{14}N$ (99.64%) and $^{15}N$ (0.36%). Nitrogen is unusual in that the most abundant isotope has an uneven number of neutrons (7). As nitrogen moves through the biosphere and hydrosphere, fractionation of these two isotopes can take place during chemical and physical reactions, resulting in different substances with different abundances of each isotope. Nitrogen isotopes can therefore be used as tracers to determine the path taken by nitrogen compounds through inorganic, organic and biological processes. As there is already a large difference in the concentrations of the two isotopes, the relative change in concentrations, compared to a standard, provides a much better measure of the isotope ratios in different substances than absolute amounts of each isotope. $\delta^{15}N$ is a measure of the deviation in the $^{15}N/^{14}N$ ratio in samples, compared to a standard. For this purpose, the standard used is the atmosphere (AIR), and the isotopic abundances are reported in delta (δ) units in parts per thousand (‰) deviation from the standard:

$$\delta^{15}N_{sample} = 1000 \times \left( \left( {^{15}N}/{^{14}N}_{sample} \div {^{15}N}/{^{14}N}_{standard(AIR)} \right) - 1 \right)$$

The $\delta^{15}N$ values of the various sources of nitrate vary such that some of the sources may be identified, but others may have a substantial overlap in values.[8] This variation in isotope composition has been used to recognise the type of activity responsible for nitrate in water resources[10], be it natural or anthropogenic[7,8], or even to distinguish the type of anthropogenic source, such as that done by Costanzo et al.[11] to identify sewage affecting the marine environment. A complicating factor is the fractionation between the dissolved nitrogen species being used by the plants (e.g. nitrate and ammonia) and the nitrogen compounds in the plants themselves. However, Deutsch and Voss[12] showed that minimal isotope fractionation occurs during uptake of nitrogen by aquatic plants. Similarly, Lee et al.[13] found fractionation between the dissolved species in water and various trophic levels of organism (mussels and fish) to be minor, meaning the $\delta^{15}N$ values in organisms approximately represent the $\delta^{15}N$ values of the source dissolved species.

Water quality has been a problem in the Hartbeespoort Reservoir for a long time, due to the catchment being largely affected by human activity, including agriculture, mining, industry and urbanisation.[14] Research on pollution of the reservoir has been done over the years, including on phosphorus[15], organic contaminants (PAH – polycyclic aromatic hydrocarbons and PCB – polychlorinated biphenyls)[16] and source attribution from acid mine waters[17]. Recent work shows that water quality problems, including algal blooms, are still dire and many water quality parameters exceed irrigation guidelines.[18]

Water hyacinth (*Eichhornia crassipes*) is a floating freshwater plant originally from South America; it is an aggressive invader in warm regions, and is the world's worst invasive aquatic plant.[19,20] The plant was introduced to South Africa about 100 years ago as an ornamental garden plant and is now a well-established weed in many waterways. Water hyacinth has been a serious problem in Hartbeespoort Reservoir for many decades, causing reduction in recreational usage of the waterbody, reduction in light and increase in consumption of oxygen, that together limit growth of other organisms.[21,22] It is well known that water hyacinth prefers warm, nutrient-rich water to grow in and experiments have shown that nutrient concentrations are the primary determinant of growth rates.[23]

Previous work on the water quality of the Hartbeespoort Reservoir used flow rates and analysis of nitrogen (N) and phosphorus (P) content of tributaries, including effluent from sewage works, to determine that sewage works are the primary source of N and P.[24] However, as shown in the same study, N and P concentrations decreased substantially over the length of river flow from the Kempton Park sewage works in Johannesburg to the Rietvlei Reservoir south of Pretoria, which lies on the Hennops River, a tributary of the Crocodile and therefore also the Hartbeespoort Reservoir. Significant contributions of N and P from agricultural and urban drainage may therefore be offsetting declines in original sewage contributions. The extent to which sewage works contribute to the total N and P load flowing into Hartbeespoort, and other reservoirs, can benefit from further work.

In this study, we aimed to use nitrogen isotopes of water hyacinth in the Hartbeespoort Reservoir as a new line of evidence to support the generally held view that sewage works are the primary cause of the hypertrophic state of the water body.

## Study area

The Hartbeespoort Reservoir is situated in the North-West Province of South Africa, about 30 km west of Pretoria. The dam is built into the quartzite that forms the mountainous ridge of the Magaliesberg, with the water of the northwards flowing Crocodile River backing up to the south of the ridge (see Figure 1).

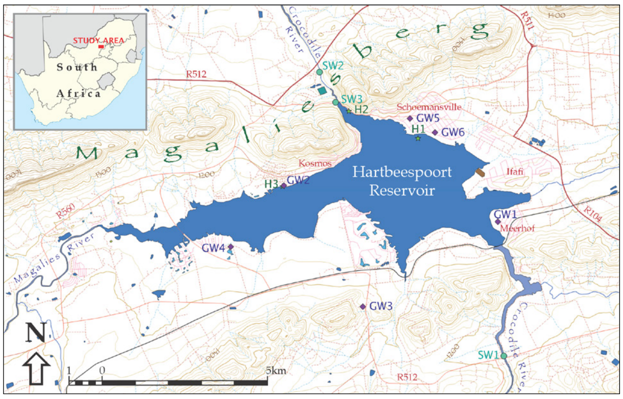


**Figure 1:** Map of the study area, showing sample locations. See Table 1 for an explanation of the sample codes.

### *Geology*

The geology of the region is dominated by the Pretoria Group of the Transvaal Supergroup, a well-preserved, relatively undeformed Archaean to Proterozoic sequence of metamorphosed volcano-sedimentary rocks.[25] Large volumes of concordant, mafic sills occur within the stratigraphy. In the vicinity of the Hartbeespoort Reservoir, the geology strikes east-west and dips gently northwards, a tilting caused by gravitational warping of the crust when the Bushveld Igneous Complex intruded to the north, cooled and subsided. The Hartbeespoort Reservoir is sited on shale of the Silverton Formation and mafic sills. To the south and north occur quartzite ridges of the Daspoort and Magaliesberg Formations, respectively, with the latter being the rock used to site and anchor the dam wall. To the south, lower in the stratigraphy of the Pretoria Group, andesite, shale, sandstone and other rock types are found, and further south dolomite of the Malmani Subgroup of the Chuniespoort Group is also found.[26] Even further south in the Johannesburg area, the catchment is underlain by granite-gneiss terrain, minor greenstones and quartzites of the Witwatersrand Supergroup. To the north of the Magaliesberg Formation lie the coarse-grained mafic and ultramafic rocks of the Bushveld Igneous Complex.

The area is faulted, with the dominant faults being two NNW-SSE striking normal faults that create a graben structure, displacing the Magaliesberg ridge visibly southwards (see Figure 1) and causing the gap through which the Crocodile River flows and where the Hartbeespoort Dam was built.[27]

### *Climate*

The region experiences a seasonal, dry subtropical climate with convective summer rain. Daily minimum to maximum temperatures average 5 °C to 24 °C in winter (May to July) and 16 °C to 30 °C in summer (November to January)[28] (Figure 2). Frost does occur on winter mornings, but is uncommon. The rainy season typically commences in October and extends until March or April, and the mean annual rainfall is about 670 mm, with most of this associated with thunderstorms. Winds are very light, except for downdraughts during thunderstorms.[29]

### *Hydrology*

The Hartbeespoort catchment is 4144 km$^2$ in size and extends southwards from the dam, incorporating the Crocodile River (including the Jukskei and Hennops Rivers) and Magalies River, as well as the minor, non-perennial Leeuspruit and Swartspruit streams.[24] The Hartbeespoort Dam was completed in 1923 and, after raising the wall in 1971, now stores 195 GL when full, with an average depth of 9.6 m.[30] The flows of the tributaries have been substantially altered by urban, agricultural and industrial activity. In particular, winter (dry season) flows are larger than natural flows due to continuous urban stormwater and sewage inputs.

### *Hydrogeology*

The area has several different types of aquifers. Near the surface, primary porosity is developed in surficial deposits (alluvium and colluvium) and weathered material.[31] Adjacent to the reservoir, the quartzites of the Pretoria Group are fractured and provide a secondary porosity aquifer of reasonable yield. Further south, the high-yielding Malmani Subgroup dolomite aquifer occurs.

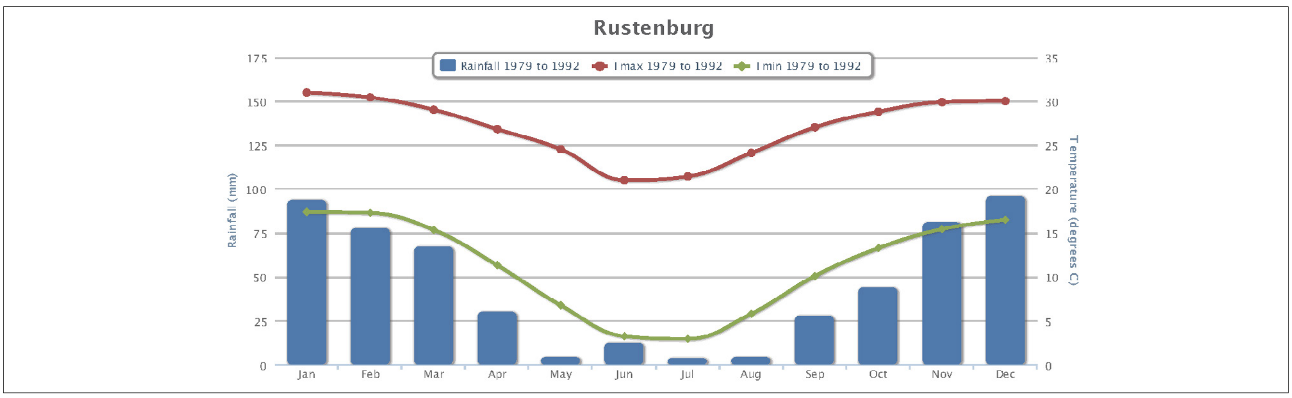


**Figure 2:** Temperature and rainfall averages for Rustenburg, 40 km northwest of the study area.[28]

Groundwater quality is generally good, but with localised pollution or risk of pollution, due to the highly populated character of the area.[31]

## Methods

For details of the sampling locations, refer to Figure 1 and Table 1. Surface water was sampled at four locations: a short distance upstream of the reservoir in the Crocodile River, a short distance downstream of the dam in the Crocodile River, and in the reservoir at the wall at surface and at 15 m depth. Groundwater was sampled from six boreholes located all around the reservoir, from very nearby, to almost 2 km away. Water hyacinth was sampled at three locations, and duplicates were taken at each location.

Water samples were analysed in the field using ExTech field probes for temperature, electrical conductivity (EC), pH, redox potential (Eh) and dissolved oxygen. Samples were taken and a lab analysis was conducted for microbial parameters and stable isotopes. Water samples were analysed for faecal coliforms and Escherichia coli at the CSIR Pretoria laboratory. An appropriate volume of water sample (250–500 mL) was filtered through a membrane filter upon which bacteria were entrapped. The filter was then placed on a selective growth medium and incubated at 44.5 °C for 18–24 h, after which colonies characteristic of faecal coliforms were counted. The number of faecal coliforms is reported per 100 mL of the original sample. Colonies from the membranes in the test for faecal coliforms were then picked and inoculated into tubes containing tryptone water. The tubes/bottles were then incubated at 44.5 °C±1 °C for 24 h. After incubation, Kovac's reagent was added. Tubes producing a red layer were positive for *E. coli*.

**Table 1:** Sample locations and descriptions

| ID | Sample type | Location | Latitude | Longitude |
|---|---|---|---|---|
| H1 | Hyacinth | Schoemansville Oewer Club | 25° 44' 08" S | 27° 52' 14" E |
| H2 | Hyacinth | Scott Street (R104) | 25° 43' 41" S | 27° 51' 05" E |
| H3 | Hyacinth | Metsi A Me offices | 25° 44' 56" S | 27° 49' 59" E |
| SW1 | Surface Water | Crocodile River upstream of reservoir | 25° 47' 45" S | 27° 53' 40" E |
| SW2 | Surface Water | Crocodile River down stream of reservoir | 25° 43' 02" S | 27° 50' 36" E |
| SW3.1 | Surface Water | Above dam at surface | 25° 43' 32" S | 27° 50' 52" E |
| SW3.2 | Surface Water | Above dam at 15 m depth | 25° 43' 32" S | 27° 50' 52" E |
| GW1 | Groundwater | Meerhof School | 25° 45' 31" S | 27° 53' 34" E |
| GW2 | Groundwater | Metsi A Me offices | 25° 44' 55" S | 27° 50' 00" E |
| GW3 | Groundwater | African Swiss Restaurant | 25° 46' 56" S | 27° 51' 19" E |
| GW4 | Groundwater | Lakeland Estate | 25° 45' 56" S | 27° 49' 07" E |
| GW5 | Groundwater | Schoemansville | 25° 43' 48" S | 27° 52' 06" E |
| GW6 | Groundwater | Schoemansville | 25° 44' 02" S | 27° 52' 31" E |

Stable hydrogen and oxygen isotopes were analysed at the University of Pretoria. Each water sample was extracted into a 5-mL container and labelled prior to the isotope analyses. The water samples were run using a Los Gatos Research laser cavity ringdown instrument. Five working standards were used to calibrate the results: LGR Working Std 1 ($\delta^2$H=-154.1‰, $\delta^{18}$O=-19.57‰), LGR Working Std 2 ($\delta^2$H=-117‰, $\delta^{18}$O=-15.55‰), LGR Working Std 3 ($\delta^2$H=-79‰, $\delta^{18}$O=-11.54‰), LGR Working Std 4 ($\delta^2$H=-43.6‰, $\delta^{18}$O=-7.14‰), and LGR Working Std 5 ($\delta^2$H=-9.8‰, $\delta^{18}$O=-2.96‰).

The water hyacinth samples were separated into roots, stems and leaves, left in an oven to dry at 70 °C for 48 h and crushed into a powder. About 1.1–1.2 mg of the powder was loaded into tin capsules pre-cleaned in toluene, combusted at 1020 °C in a Flash EA1112 elemental analyser and fed, via a ConFlo IV system, directly into a Delta V Plus stable light isotope mass spectrometer. Laboratory standards Merck Gel ($\delta^{13}$C=-20.26‰, $\delta^{15}$N=7.89‰, C=41.28%, N=15.29%) and DL-Valine ($\delta^{13}$C=-10.57‰, $\delta^{15}$N=-6.15‰, C=55.50%, N=11.86%) were used and a blank sample was run after every 11 unknown samples.

## Results and discussion

### *Water quality*

The water quality and stable isotope results are shown in Table 2 and the water hyacinth analyses in Table 3. The pH of the water is neutral to slightly alkaline, with surface water having the more alkaline values, but all samples are well within drinking water guidelines of 6.0–9.0[32] (Figure 3). The EC (measured as mS/m) also shows the samples are fresh water, generally acceptable for drinking (Figure 3).[32] The total dissolved solids was calculated from the EC by the ExTech field probe, and so is an approximation. The freshest water (279 mg/L) was found in GW3, the borehole to the south of the reservoir, and probably reflects freshly recharged groundwater from the Witwatersberg hills to the south, which comprise Daspoort Formation quartzite. Fast flow through fractures and the lack of chemical input from weathering due to the quartzitic rock probably account for the freshness of the groundwater in this borehole. The highest dissolved content occurs in GW5, northeast of the reservoir in Schoemansville and is probably due to this borehole being drilled into the Silverton Formation, a shale dominated layer, which encourages evaporation prior to recharge and causes addition of dissolved matter from weathering and concentration of this dissolved matter by slow groundwater flow.

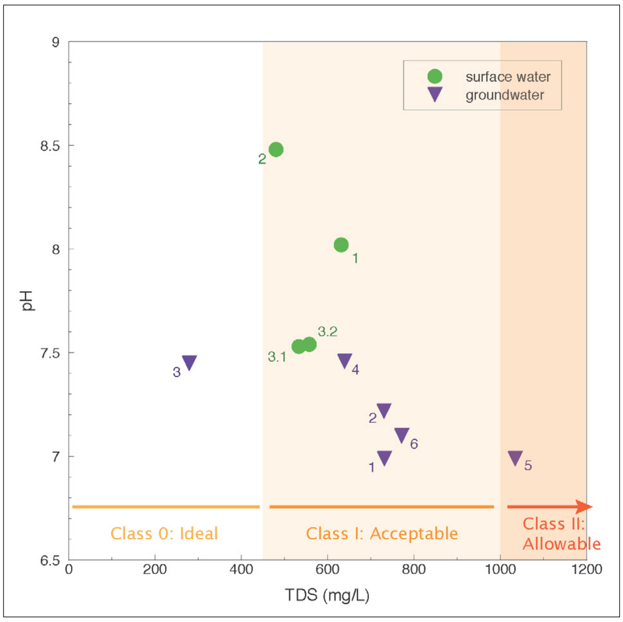


**Figure 3:** TDS (total dissolved solids) and pH values for groundwater and surface water with the SANS 241 water quality guideline values shown.[27] The pH is acceptable throughout.

Based on the microbiological analyses, the groundwater appears safe to drink; however, the surface water is not. The inflowing water from the Crocodile River is the most polluted by microbes, with outflowing reservoir water less so, and, interestingly, the water in the reservoir appears to have no coliforms. This is perhaps due to competition with algae or hyacinth, or consumption by other microbes, or destruction by sunlight (UV radiation).

### *Water stable isotopes*

The stable isotopes of water show a very clear differentiation between the groundwater and surface water samples. The surface water samples are relatively enriched in the heavier isotopes, and plot to the right of

**Table 2:** Water quality and stable isotope results for groundwater and surface water samples

| Sample | T | pH | EC | TDS | DO | Eh | δD | δ¹⁸O | FC | *E. coli* |
|---|---|---|---|---|---|---|---|---|---|---|
| | °C | | mS/m | mg/L | mg/L | mV | ‰ | ‰ | /100 mL | /100 mL |
| GW1 | 22.2 | 6.9 | 104 | 731 | 1.84 | 160 | -11.9 | -3.15 | <1 | <1 |
| GW2 | 20.0 | 7.2 | 99 | 730 | 2.88 | 163 | -21.5 | -4.58 | <1 | <1 |
| GW3 | 23.8 | 7.4 | 40 | 279 | 4.74 | 168 | -28.9 | -5.90 | <1 | <1 |
| GW4 | 20.8 | 7.5 | 88 | 639 | 4.70 | 170 | -14.9 | -3.38 | <1 | <1 |
| GW5 | 21.0 | 7.0 | 143 | 1034 | 4.88 | 163 | -7.4 | -2.92 | <1 | <1 |
| GW6 | 21.9 | 7.1 | 110 | 771 | 2.60 | 160 | -17.4 | -3.72 | <1 | <1 |
| SW1 | 17.9 | 8.0 | 79 | 631 | 3.56 | 176 | -4.5 | -0.98 | 1400 | 420 |
| SW2 | 17.5 | 8.5 | 66 | 480 | 5.60 | 152 | +1.1 | -0.85 | 41 | 41 |
| SW3.1 | 18.3 | 7.5 | 79 | 533 | 2.92 | 151 | +2.8 | -0.90 | <1 | <1 |
| SW3.2 | 17.9 | 7.5 | 78 | 557 | 2.40 | 160 | +0.3 | -1.03 | <1 | <1 |

*T, temperature; EC, electrical conductivity; TDS, total dissolved solids; DO, dissolved oxygen; Eh, redox potential; FC, faecal coliforms*
*TDS was calculated from EC*

the local meteoric water line (LWML), which here is the Johannesburg LMWL[33] (Figure 4). This is a sign of evaporation having taken place since precipitation occurred, which is to be expected for water in rivers and reservoirs.[34] The groundwater samples all plot close to the JLMWL, which is a sign that minimal evaporation takes place prior to recharge. Interestingly, GW3 has the most negative δ values. This is usually a sign of either recharge at higher altitude (an isotopic altitude effect), or heavy rainfall events (an isotopic amount effect).[35] Recharge on top of the Witwatersberg could account for a part of this, as the slightly higher, cooler and wetter location on top of this ridge would drive the isotope composition of precipitation (and therefore recharge) towards more negative δ values. This confirms the conclusions drawn from the chemistry data, that this borehole contains groundwater that was recharged faster, through fractures in the quartzite of the Daspoort Formation.

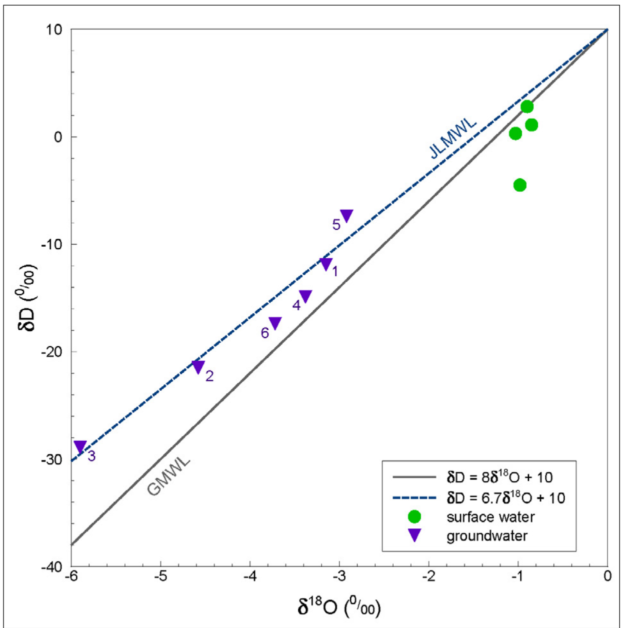


**Figure 4:** Stable isotope composition of surface and groundwater samples, with the Johannesburg Local Meteoric Water Line (JLMWL)[33] and Global Meteoric Water Line (GMWL)[37] shown for reference.

### *Water hyacinth stable isotopes*

Table 3 and Figure 5 show the C and N stable isotope results for the water hyacinth samples. It can be seen in Table 3 that there is little variation in the $\delta^{13}C$ values, the range being 25–30‰, and they fall into the typical range for C3 metabolism plants. The $\delta^{15}N$ values range from 20‰ to 33‰, with an average of 26.4‰. The values are displayed in Figure 5, where it is apparent that there is no systematic variation, either by sample location, or by plant part.

**Table 3:** Water hyacinth stable isotope analyses

| Sample | Weight | δ¹⁵N | N | δ¹³C | C | C/N |
|---|---|---|---|---|---|---|
| | g | ‰ | % | ‰ | % | |
| 1.1R | 1.12 | 23.13 | 3.3 | -25.79 | 38.5 | 13.5 |
| 1.2R | 1.18 | 32.53 | 3.0 | -28.34 | 35.9 | 13.9 |
| 2.1R | 1.17 | 30.87 | 3.1 | -26.00 | 38.8 | 14.6 |
| 2.2R | 1.13 | 28.71 | 2.4 | -27.26 | 40.6 | 19.7 |
| 3.1R | 1.16 | 26.21 | 2.6 | -27.50 | 41.2 | 18.5 |
| 3.2R | 1.15 | 20.90 | 2.7 | -25.35 | 38.3 | 16.7 |
| **Mean R** | **1.15** | **27.06** | **2.8** | **-26.71** | **38.9** | **16.2** |
| 1.1S | 1.16 | 22.55 | 3.3 | -27.08 | 34.1 | 12.1 |
| 1.2S | 1.14 | 29.04 | 2.5 | -27.98 | 34.4 | 15.8 |
| 2.1S | 1.18 | 29.10 | 1.9 | -26.70 | 35.1 | 21.4 |
| 2.2S | 1.12 | 27.68 | 1.9 | -29.60 | 36.6 | 22.8 |
| 3.1S | 1.17 | 24.81 | 1.9 | -28.10 | 35.8 | 22.2 |
| 3.2S | 1.13 | 21.78 | 2.6 | -27.22 | 38.4 | 17.3 |
| **Mean S** | **1.15** | **25.83** | **2.3** | **-27.78** | **35.7** | **18.6** |
| 1.1L | 1.18 | 20.89 | 4.9 | -27.15 | 43.2 | 10.2 |
| 1.2L | 1.11 | 33.39 | 3.9 | -28.60 | 42.0 | 12.6 |
| 2.1L | 1.13 | 31.64 | 4.1 | -27.52 | 42.6 | 12.2 |
| 2.2L | 1.16 | 28.83 | 3.4 | -29.89 | 41.5 | 14.1 |
| 3.1L | 1.16 | 22.24 | 3.6 | -28.28 | 41.9 | 13.4 |
| 3.2L | 1.13 | 20.35 | 4.2 | -26.69 | 42.9 | 11.9 |
| **Mean L** | **1.15** | **26.22** | **4.0** | **-28.02** | **42.3** | **12.4** |

Plants take up nitrogen as dissolved species, such as nitrate or ammonia, in soil water, or, in the case of aquatic plants, from surface water. The $\delta^{15}N$ in a plant will therefore reflect the $\delta^{15}N$ of the dissolved species, but not be exactly the same, due to fractionation. Fractionation is dependent upon factors such as concentration of the dissolved species, water movement, temperature and organism specific factors. However, Deutsch and Voss[12] and Lee et al.[13] showed that, generally, fractionation is minor and the resultant $\delta^{15}N$ values in organisms reflect approximately that of the original dissolved species in the water.

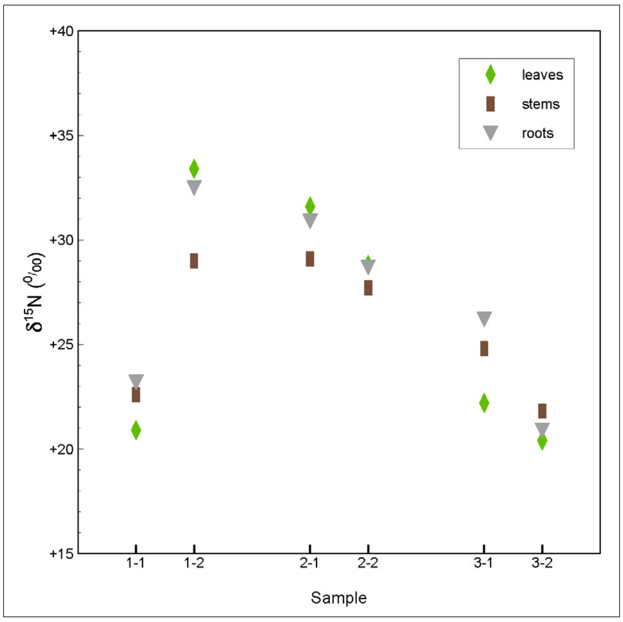


**Figure 5:** Nitrogen isotope composition of water hyacinth from Hartbeespoort Reservoir.

Figure 6 shows the variation in $\delta^{15}N$ values across a range of different natural and synthetic materials, as well as the water hyacinth analyses from this study. The results from this study plot outside most of the known ranges, but are closest to that for sewage or manure. This confirms the assertions of previous researchers that the main factor causing poor water quality in Hartbeespoort Reservoir is effluent from sewage works, mainly those servicing Johannesburg.[36]

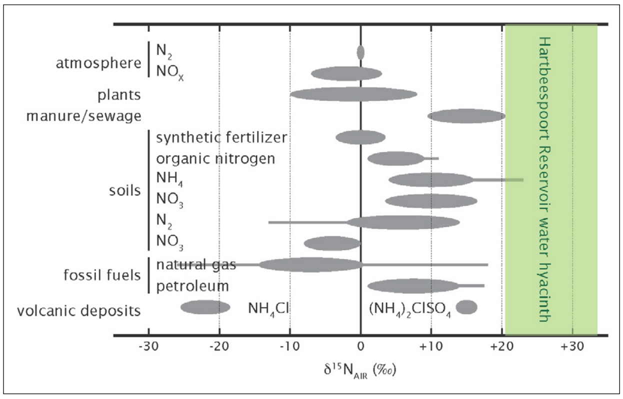


**Figure 6:** Diagram showing the nitrogen isotope composition of various materials.[38]

## Conclusions

Simple water quality parameters such as EC (40–140 mS/m) and pH (6.9–8.5) are within acceptable ranges in surface water and groundwater of the Hartbeespoort Dam area; however, faecal coliforms and *E. coli* measurements show the surface water, particularly the inflowing Crocodile River, to be high risk to human health. The relatively fresh nature of the water indicates minimal contribution from industrial or mine effluents, including acid mine drainage, which usually have elevated EC values and, in the case of acid mine drainage, low pH.

Stable isotopes of water (H and O) reveal evaporated surface waters and a variation in groundwater due to the varied geology and landscapes of the area. The clear divide between the δD and $\delta^{18}O$ values for groundwater and surface water show that the Hartbeespoort Reservoir is primarily surface water fed, with negligible groundwater input.

Nitrogen isotopes of water hyacinth reflect the isotope composition of the dissolved nitrogen species (nitrate etc.) in the reservoir. The $d^{15}N$ averages 26‰, which matches most closely to that for manure or sewage. This confirms assertions of previous researchers that sewage works, mostly those servicing Johannesburg, are the primary cause of poor water quality in the Hartbeespoort Reservoir. As high nutrient levels are the main determinant of water hyacinth growth rates[23] and manual, chemical and biological control struggle to control the infestations, it is clear that any water hyacinth control efforts should target sanitation in informal settlements and the various sewage treatment works flowing into the Crocodile River catchment.

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## Competing interests

We have no competing interests to declare.

## Authors' contributions

R.G.: Conceptualisation, field work, initial analysis and writing. R.D.: Conceptualisation, some field work, funding, final analysis and article writing (including graphics).

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# Modelling water temperature in the lower Olifants River and the implications for climate change

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Freshwater systems in southern Africa are under threat of climate change, not only from altered flow regimes as rainfall patterns change, but also from biologically significant increases in water temperature. Statistical models can predict water temperatures from air temperatures, and air temperatures may rise by up to 7 °C by 2100. Statistical water temperature models require less data input than physical models, which is particularly useful in data deficient regions. We validated a statistical water temperature model in the lower Olifants River, South Africa, and verified its spatial applicability in the upper Klaserie River. Monthly and daily temporal scale calibrations and validations were conducted. The results show that simulated water temperatures in all cases closely mimicked those of the observed data for both temporal resolutions and across sites (NSE>0.75 for the Olifants River and NSE>0.8 for the Klaserie). Overall, the model performed better at a monthly than a daily scale, while generally underestimating from the observed (indicated by negative percentage bias values). The statistical models can be used to predict water temperature variance using air temperature and this use can have implications for future climate projections and the effects climate change will have on aquatic species.

**Significance:**

- Statistical modelling can be used to simulate water temperature variance from observed air temperature, which has implications for future projections and climate change scenarios.
- While there are many other factors affecting water temperature, air temperature accounts for up to 95% of water temperature variance.
- The model used can successfully simulate water temperature variance for different rivers.

## Introduction

Freshwater systems face compound effects of direct anthropogenic disturbances and climate change, making them among the most vulnerable ecosystems.[1-5] Climate change and the consequential rise in water temperature has had many adverse effects on freshwater fish communities, including disrupting trophic inter-dependencies, changing phenology, losses in species richness and diversity, mass mortality events, and extinctions.[1,6-10] In subtropical southern Africa, warming is predicted to occur at more than double that of the global rate, and annual-average near-surface temperatures are predicted to rise by 6 °C by 2100.[11] The intergovernmental panel on climate change (IPCC) released a sixth assessment report under the RCP8.5 scenario to forecast future temperature changes, and a mean air temperature rise of 4–7 °C is anticipated, while the maximum air temperatures are predicted to rise by 4–8 °C in southern Africa by the end of the century.[12] This rise is compounded with a forecast of up to 40% less summer rainfall in southern Africa where evaporation rates can be as high as 65%, which will decrease effective rainfall.[13] Higher temperatures and lower effective rainfall, in conjunction with an increase in associated extreme drought events and the increasing demand for fresh water from a growing human population, is a concern for the persistence of freshwater ecosystems and their associated fauna.[11,14] For example, freshwater fish inhabit the upper limits of their thermal tolerance and will not be able to move or evolve fast enough to track climate change; therefore, the effects of rising temperatures will be detrimental to these taxa.[1]

Forecasts of water temperature in freshwater rivers and streams have assimilated physical, statistical, and ensemble water temperature models.[15-20] An example of a physical model is the semi-Lagrangian River Basin Model (RIC) developed by Yearsley[16] to solve time-dependent equations for the thermal energy budget in rivers. It can be used to model climate change in rivers and integrate a macro-scale hydraulic model called variable infiltration capacity.[15] Both models require large amounts of data and many parameters that include solar and long-wavelength radiation, humidity, soil type, elevation, land cover, precipitation and various river channel parameters, making them data-intensive and constrained by model parameter availability.[15-17] Statistical water temperature models use variables such as air temperature to estimate current and/or future water temperatures. Although both linear and non-linear regression models have been developed in the pursuit of modelling water temperature using air temperature[21,22], linear models are more accurate and produce a better fit[23]. These types of statistical models require less data input than physical models and are easier to execute.[17]

The aim of this study was to use statistical models based on historical data to calibrate and validate water temperature models in the lower Olifants River, South Africa. The lower Olifants River is a higher-order river that runs through South Africa's largest national park, the Kruger National Park, and supplies water to both South Africa and Mozambique.[24] This region is water stressed, as the Olifants River Basin has been heavily exploited and over-abstracted.[25] Southern African rivers have unique thermal and morphological characteristics, and the use of statistical models developed on northern-hemisphere rivers is problematic.[26] We follow the framework of a statistical linear regression model developed by Rivers-Moore et al.[20], which has been used to simulate water temperature in four other freshwater rivers in South Africa. The framework uses four options, with varying parameters: (1) air temperature parameters only, (2) air temperature parameters and flow, (3) air temperature parameters and relative humidity, and (4) air temperature parameters, flow, and relative humidity. The previous applications of this approach found that air temperature had the most significant influence, and that flow and relative humidity reduced model accuracy.[20] We validated the model using a second river within the Olifants River Basin – the upper Klaserie River.

This site is at a higher altitude and observed data are expected to be lower than those of the Olifants River. We aimed to test whether the statistical model was equal in efficacy for the Olifants and Klaserie Rivers and predicted that the simulated outputs would be similar for both rivers.

## Methods

Hourly air temperature data were obtained from weather stations of the South African Weather Service at Phalaborwa (station number 0681266E6; 23°56'24" S, 31°10'12" E), Hoedspruit (0638081_1; 24°21'0'' S, 31°3'0'' E), and Giyani (0724318_9; 23°18'36'' S, 30°40'48'' E), in Limpopo Province, South Africa (Figure 1). Hourly water temperature data were collected from a depth of ~1 m in the Olifants River at Mamba Weir (24°3'59.86" S, 31°14'33.6" E, Figure 1) from 7 August 2015 to 6 February 2020 using an Aqua TROLL 200 logger (In-Situ Inc., Fort Collins, Colorado, USA). To further validate the model, data from a second river, the upper Klaserie River (24°35'16.46" S, 30°52'48.80" E, Figure 1) within the Olifants River system were used. Hourly water temperature data were collected just above the riverbed using a HOBO pendant temperature logger (Onset Computer Corporation, Cape Cod, Massachusetts, USA).

### *Calibrating the model*

The air temperature data from the Hoedspruit weather station were primarily used and supplemented by data from Phalaborwa and Giyani. Mean daily, mean monthly, minimum monthly, and minimum daily temperatures were calculated. The general regression model from Rivers-Moore et al.[20] based on correlations between minimum and average air temperatures and the average water temperature (Equation 1) was adapted for this study:

$$WT_{max} = (AT_{avg} * a) + (AT_{min} * b) + c \,, \qquad \text{Equation 1}$$

where $WT_{max}$ = maximum water temperature, $AT_{avg}$ = mean air temperature, $AT_{min}$ = minimum air temperature, $a$ = mean air temperature coefficient, $b$ = minimum air temperature coefficient, and $c$ = regression constant.

Both monthly and daily data sets were calibrated using August 2015 to November 2017 water temperature data from Mamba Weir. Periods without observed data were deleted to create the best model fit. The parameters were deduced by keeping *b* and *c* constant while changing the value of *a*, and then repeating this process with *b* and *c*. Parameter *a* relates mean air temperature to mean water temperature while *b* reduces the effects of high diurnal air temperatures (minimum and maximum) on $WT_{max}$. The set of constants was chosen based on the appearance of the hydrothermograph, the calculated residuals (i.e. the difference between simulated and observed water temperature) and the highest Nash–Sutcliffe efficiency (NSE) that represents an indicator of how well the observed *versus* the simulated data fit the 1:1 line.[27]

### *Model evaluation statistics*

The statistical analyses of Moriasi et al.[28] were used in addition to the hydrothermographs to evaluate the model performance. These statistical analyses included: the NSE (Equation 2); the coefficient of determination ($R^2$) showing the degree of variance between the simulated and observed data sets, which ranges between 0 and 1 (Equation 3); the percentage bias (PBIAS) which measures the average likelihood for the simulated data to be higher or lower than the observed data (Equation 4); the root mean square error (RMSE; Equation 5) which is used to calculate the observations standard deviation ratio (RSR; Equation 6) and combines error index statistics and scaling factors by standardising the RMSE using the standard deviation of the observed data as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{n} (Y_{obs,i} - Y_{sim,i})^2}{\sum_{i=1}^{n} (Y_{obs,i} - Y_{obs,mean})^2} \,, \qquad \text{Equation 2}$$

$$R^2 = \frac{\sum_{i=1}^{n} (T_{obs,i} - T_{obs,mean})(T_{sim,i} - T_{sim,mean})}{\sqrt{\sum_{i=1}^{n} (T_{obs,i} - T_{obs,mean})^2 \sum_{i=1}^{n} (T_{sim,i} - T_{sim,mean})^2}} \qquad \text{Equation 3}$$

$$PBIAS = \frac{\sum_{i=1}^{n} (Y_{obs,i} - Y_{sim,i}) \times 100}{\sum_{i=1}^{n} (Y_{obs,i})} \,, \qquad \text{Equation 4}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (Y_{sim,i} - Y_{obs,i})^2}{n-4}} \,, \qquad \text{Equation 5}$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^{n} (Y_{obs,i} - Y_{sim,i})^2}}{\sqrt{\sum_{i=1}^{n} (Y_{obs,i} - Y_{mean})^2}} \,, \qquad \text{Equation 6}$$

where $Y_{obs}$ = the observed temperature, $Y_{sim}$ = the simulated temperature, $Y_{obs,mean}$ = the mean of observed data for the constituent being evaluated, $Y_{sim,mean}$ = the mean of the simulated data for the constituent being evaluated, and $n$ = the total number of observations.

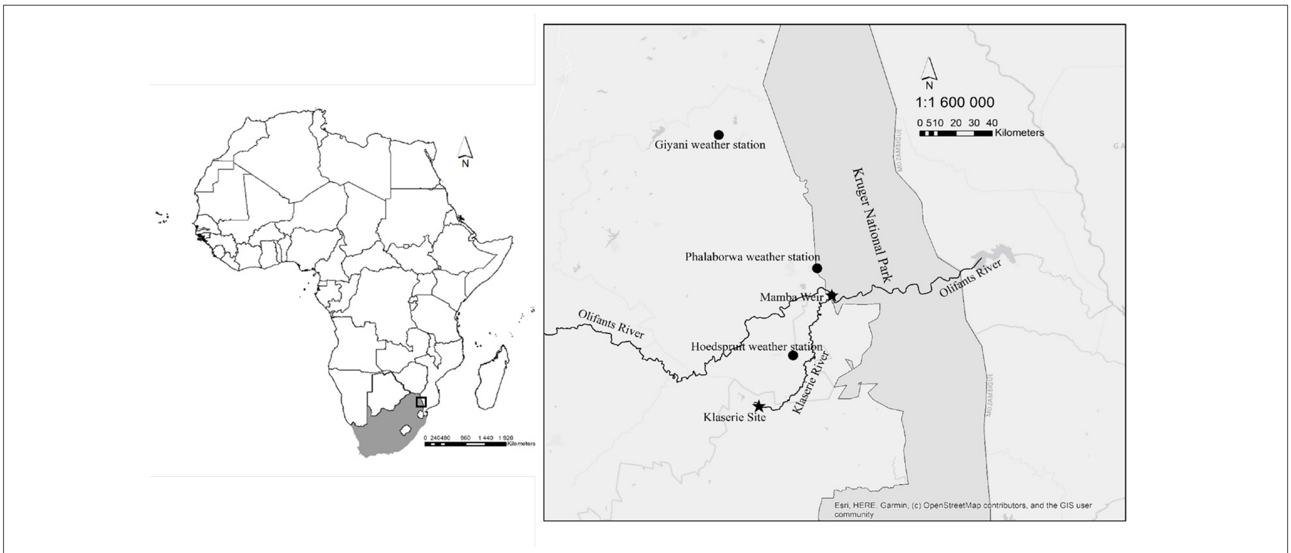


**Figure 1:** Map of study site (with an insert of Africa highlighting South Africa) showing Mamba Weir in the lower Olifants River in Kruger National Park, Limpopo Province; the Klaserie site in the upper Klaserie River, Mpumalanga Province; and three weather stations (Hoedspruit, Phalaborwa and Giyani), across Limpopo Province; and where air temperature measurements were taken for the study.

## Results

Hydrothermographs were generated for calibration and validation data for daily and monthly timescales for Mamba Weir (Figure 2 A–D) using Equation 1 and the following constants: $a = 0.900$, $b = 0.132$, and $c = 1.600$, and for daily and monthly timescales for Klaserie River (Figure 3 A,B) using the model Equation 1 that generated the following constants: $a = 0.600$, $b = 0.132$, and $c = 1.700$.

Figure 2A shows the calibration hydrothermograph for Mamba Weir using monthly mean water temperature from August 2015 to November 2017. The mean observed water temperature was 23.70±3.32 °C, while the mean simulated water temperature was 23.95±2.96 °C. Both observed and simulated hydrographs produced a strong seasonal water temperature pattern (Figure 2A). The model evaluation statistics performed for each model (Table 1) show that the residuals for monthly mean water temperature from August 2015 to November 2017 are on average 0.25±0.77 °C. The NSE and $R^2$ are very good at 0.94 and 0.95, respectively (Table 1). PBIAS is -1.04% (Table 1), indicating that simulated data are on average below those of the observed, which can also be seen in Figure 2A. The RMSE and RSR values are low at 0.79 and 0.24, respectively (Table 1).

Figure 2B shows the hydrothermograph for Mamba Weir using monthly mean and simulated water temperatures for the validation period December 2017 to February 2020. Mean observed water temperature was 24.68±3.38 °C, while mean simulated water temperature was 24.75±3.09 °C. As expected, both observed and simulated hydrographs produced a strong seasonal pattern in water temperature with higher temperatures during summer than winter. The model evaluation statistics (Table 1) show that the residuals for monthly mean and simulated water temperatures for the validation period December 2017 to February 2020 are low, averaging 0.07±0.95 °C (Table 1). The simulated temperature is higher than the observed during winter and lower than the observed during summer months, indicating some underestimation of the extremes; however, the PBIAS is very low at -0.30%, indicating that the simulated is closely linked to the observed (Table 1). The NSE and $R^2$ are both high at 0.92 and 0.92, respectively, while the RSR is low at 0.28 (Table 1).

Figure 2C shows the hydrothermographs for average daily observed temperatures and calibration temperatures for Mamba Weir from 7 August 2015 to 3 December 2017. Average observed temperature was 23.77±3.63 °C, while the average simulated daily temperature was 24.01±3.87 °C. The model evaluation statistics (Table 1) for the average daily observed and calibration temperatures for Mamba Weir from 7 August 2015 to 3 December 2017 show that the residuals are on average 0.03±1.75 °C. The NSE and $R^2$ for the monthly calibration are lower than that of the monthly at 0.76 and 0.80, respectively; however, differences are extremely marginal (Table 1). PBIAS is -1.05% (Table 1), indicating again that simulated data are on average below those of the observed data, and the RSR is low at 0.49.

Figure 2D shows the hydrothermographs for average daily observed temperatures and simulated temperatures for Mamba Weir for the validation period 4 December 2017 to 6 February 2020. Average observed temperature was 24.53±3.76 °C while average simulated daily temperature was 24.57±3.90 °C. The model evaluation statistics (Table 1) for the average daily observed temperatures and simulated temperatures for Mamba Weir for the validation period 4 December 2017 to 6 February 2020 show that the residuals were low (0.04±1.75 °C). As with the monthly time-step, the graphic representation of the simulated and observed water temperatures are very similar, which is also supported by a low PBIAS -0.17%. There is more variation in daily temperatures of both the simulated and observed temperatures between October and January. Once again, the NSE and $R^2$ are slightly lower than the monthly time-step at 0.78 and 0.80, respectively, while RSR remains relatively low at 0.47 (Table 1).

Figure 3A shows the hydrothermograph for Klaserie River using monthly mean water temperature from March 2011 to April 2013. The mean observed water temperature was 16.00±2.80 °C, while the mean simulated water temperature was 16.18±2.56 °C. Both observed and simulated hydrographs produced a strong seasonal water temperature pattern. The residuals for monthly mean water temperature are on average 0.19±0.57 °C (Table 1). The NSE and $R^2$ are very good at 0.95 and 0.96, respectively (Table 1). PBIAS is -1.18% (Table 1), indicating simulated data plot below observed data, which can also be seen in Figure 3A. The RMSE and RSR values are low at 0.59 and 0.21, respectively (Table 1).

Figure 3B shows the hydrothermograph for Klaserie River using daily mean water temperature from March 2011 to April 2013. The mean observed water temperature was 16.09±2.95 °C, while the mean simulated water temperature was 15.76±2.92 °C. Both observed and simulated hydrographs produced a strong seasonal water temperature pattern. The residuals for monthly mean water temperature are on average 0.32±1.23 °C (Table 1). The NSE and $R^2$ are 0.81 and 0.83, respectively (Table 1). PBIAS is -2.05% (Table 1), indicating simulated data are lower than observed data, which can also be seen in Figure 3A. The RSR value is low at 0.44 (Table 1).

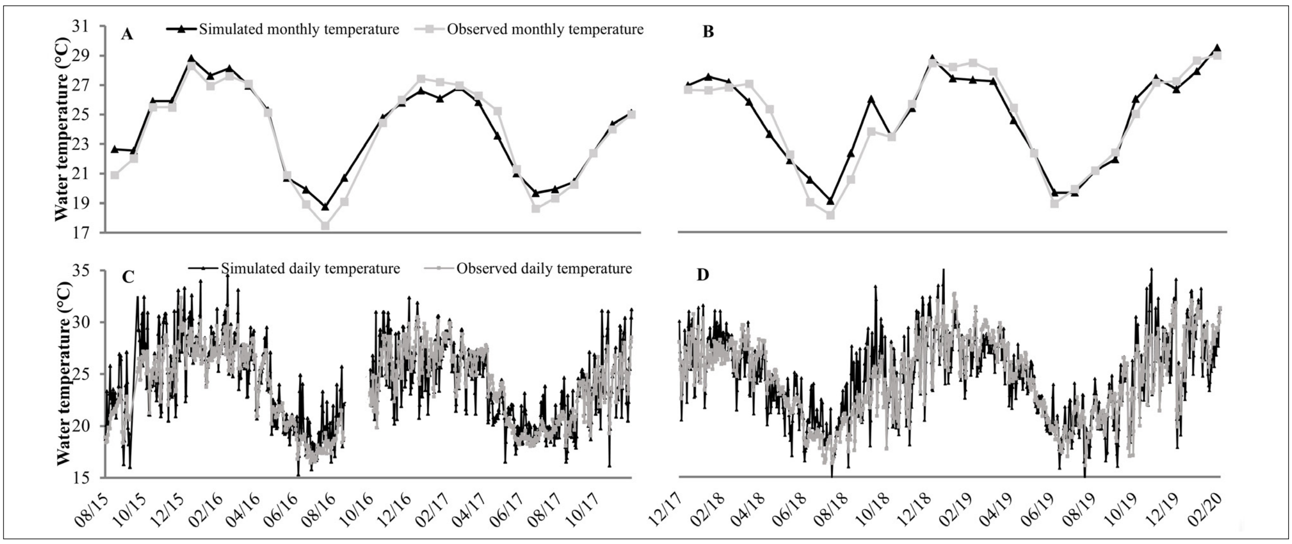


**Figure 2:** Hydrothermographs of (A, B) monthly model calibration (black) and observed (grey) water temperatures, and (C, D) daily model calibration (black) and observed (grey) water temperatures, for periods August 2015 to November 2017 (A, C) and December 2017 to February 2020 (B, D), for Mamba Weir, Olifants River, South Africa. The gap in C is due to 13 days of missing observational data during September 2016.

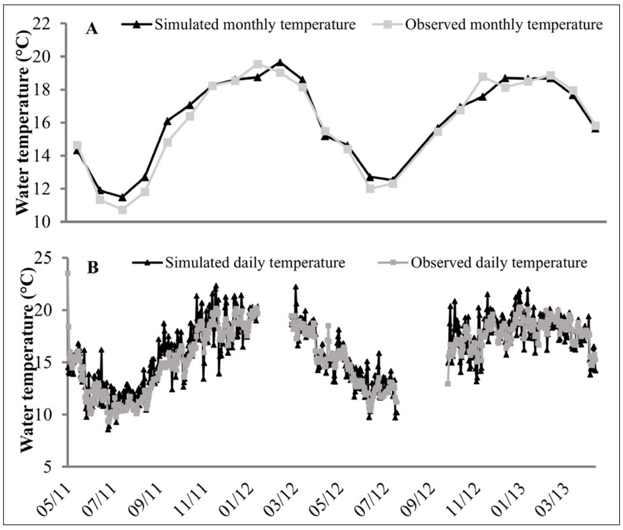


**Figure 3:** Hydrothermographs of monthly model (A) and daily model (B) for March 2011 to April 2013, both simulated (shown in black) and observed (shown in grey) water temperatures for Klaserie River, South Africa. The gaps in B are due to periods of missing observational data.

**Table 1:** Evaluation statistics for calibration and validation models of monthly and daily water temperatures at Mamba Weir

| Model | Model evaluation statistics | | | | | | |
|---|---|---|---|---|---|---|---|
| | *n* | NSE | $R^2$ | PBIAS | RMSE | RSR | Residuals |
| **Mamba Weir** | | | | | | | |
| Monthly calibration | 27 | 0.94 | 0.95 | -1.04 | 0.79 | 0.24 | 0.25 ± 0.77 |
| Monthly validation | 27 | 0.92 | 0.92 | -0.30 | 0.93 | 0.28 | 0.07 ± 0.95 |
| Daily calibration | 796 | 0.76 | 0.80 | -1.05 | 1.77 | 0.49 | 0.03 ± 1.75 |
| Daily validation | 794 | 0.78 | 0.80 | -0.17 | 1.75 | 0.47 | 0.04 ± 1.75 |
| **Klaserie River** | | | | | | | |
| Monthly | 23 | 0.95 | 0.96 | -1.18 | 0.59 | 0.21 | 0.19 ± 0.57 |
| Daily | 592 | 0.81 | 0.83 | -2.05 | 1.27 | 0.44 | 0.32 ± 1.23 |

*NSE, Nash–Sutcliffe efficiency; $R^2$, the coefficient of determination; PBIAS, percentage bias; RMSE, root mean square error; RSR, observations standard deviation ratio*

## Discussion

The model predicts water temperature variance based on air temperature with a degree of accuracy in the seasonal and diurnal time frames that is biologically relevant, for both the Mamba Wier and the upper Klaserie sites. The NSE is one of the most widely used statistics for validating water models, and many studies have found that NSE values of ≥0.6 are satisfactory, while values ≥0.75 are considered very good.[28-35] The NSE determines how closely the observed and the simulated data fit the 1:1 line and, similarly, the $R^2$ measures variance between observed and simulated which indicates the fit of the model.[28] Models such as the Hydrological Simulation Program FORTRAN (HSPF) had NSE values of between 0.6 and 0.7 for analysis of monthly water temperatures in tropical rivers of southern Malaysia.[23] This model produced NSE and $R^2$ values above 0.75 for both monthly and daily models, with monthly models performing slightly better.

The PBIAS is a measure of how often the simulated data differ from the observed data, and further has the ability to show whether the model is under- or overestimating simulating temperatures.[28,34] The results show that the simulations for both daily and monthly data sets resemble the observed data closely. The PBIAS indicates that the model tends to slightly underestimate the water temperatures, with this underestimation being more prevalent during the daily timestep, likely due to the model being unable to predict anomalous hot days. Our results are between -0.17% and -2%, whereas satisfactory PBIAS values are ±25% and very good values ±10%; therefore, our values are almost negligibly underestimating from the observed.[28] RSR incorporates the benefits of error index statistics and includes a scaling/normalisation factor.[28] A perfect model would have an RSR value of 0, indicating no residual variation and therefore low RSR and RMSE values are considered good indicators of model performance.[32] The RSR values produced are all lower than 0.5 and are considered very good.[28]

The model had a tendency to underestimate water temperatures, which must be considered in future projections. While this underestimation is very small, a conservative model for climate predictions is preferred over a more aggressive model that will give a false representation of the increase in water temperatures. This may be due to the model being over-simplistic and not incorporating variables such as river channel metrics, geology, groundwater metrics, vegetation, humidity, solar radiation, evaporation and various other parameters that may drive or influence water temperature.[26,36] However, it has been demonstrated that the addition of variables such as relative humidity, rainfall and flow in a multiple regression model had little effect on the model, and, in the case of flow, even reduced accuracy.[20] While, conversely, air temperature has been shown to be the most important driver of water temperature, and in the absence of additional data, produces a simplistic model that accurately predicts water temperatures.[20,26] Our study also demonstrates that, in the case of the two study river sites, a simple statistical model can simulate water temperature variance with accuracy and precision that is biologically relevant. This is particularly important in data-deficient regions, such as in Africa, where climate change studies on freshwater systems are important given the alarming rise in air temperature.[11] An important caveat is that, while air temperature is the only input variable to the models, the parameterisation differs between sites. This means that air temperature alone does not account universally for water temperature, and models need site-specific calibration. This shortcoming is perhaps relevant at large spatial or temporal scales, but a critical implication of the models is that diurnal and seasonal variances (as opposed to absolute values) in water temperature are strongly driven by variance in air temperature. As a first-order approximation of the impact of long-term water temperature drivers, such as climate change, on river biology, this is very useful, but for a universally applicable solution, it is necessary to invoke more complex models.

Complex models, such as multiple regression models, typically have more input parameters, making them susceptible to equifinality. Equifinality is common in hydrological models, and in this context refers to the likelihood that multiple sets of parameters will produce equivalent models.[37-40] There are sources of equifinality in models, namely over-parameterisation and errors in the observational or input data of parameters.[39,40] Errors in observational data not only cause equifinality, but also reduce accuracy[40], with the more parameters added, the more observer bias or collection errors added to the model.

The study prediction that the model would successfully simulate water temperature for both rivers was correct, despite the difference in river order and altitude. While Rivers-Moore et al.[20], as well as our study results, support the use of simple, linear statistical models in simulating water temperatures using air temperature within South African rivers, this can be applied in other river study sites where there is a deficit of data. Future studies should focus on the effects of global climate change on freshwater systems and include both the physical and biological impacts. Currently, studies on invertebrates and fish within South African rivers are showing the potential impacts of rising water temperatures on species' thermal tolerances[41-44]; modelling future water temperature of these rivers is vital towards the understanding of when these impacts will take effect and guide mitigation actions.

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## Competing interests

We have no competing interests to declare.

## Authors' contribution

A.L.A.: Conceptualisation, data analysis, writing – the initial draft. D.C.H.R.: Data analysis, validation, writing – revisions. C.T.C.: Student supervision, funding acquisition, writing – revisions. S.W.: Conceptualisation, validation, student supervision, funding acquisition, writing – revisions.

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# $CO_2$ storage potential of basaltic rocks, Mpumalanga: Implications for the Just Transition

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South Africa is the largest $CO_2$ emitter on the African continent. These emissions stem from a heavy reliance on coal as the primary energy fuel and contributor toward socio-economic development. The South African government has targeted reducing $CO_2$ emissions by more than half in the next 10 years. To meet climate change mitigation scenarios, while alleviating continued emissions, South Africa will look to technologies such as carbon capture, utilisation and storage. Initial assessments of South Africa's potential for $CO_2$ storage have focused on deep saline aquifers within volcano-sedimentary sequences along the near and offshore regions. Sustaining the Just Transition will, however, require additional storage capacity. In this study, we make an initial assessment of possible $CO_2$ storage in basaltic sequences of the Ventersdorp Supergroup. Geological and mineralogical information was ascertained from borehole data. The geological information suggests that the subsurface extent of the Ventersdorp Supergroup is at least 80 000 km$^2$ larger than previously mapped, extending beneath major point-source $CO_2$ emitters and active coalfields. Furthermore, petrographic analyses suggest pore space of up to ca 15% with minimal alteration, and preservation of mafic silicate minerals that would enable reactive carbonation of injected $CO_2$. Notable metasomatic and hydrothermal alteration is confined to significant contact horizons, such as the lowermost Ventersdorp Contact Reef. These results suggest that basaltic sequences may exponentially increase South Africa's $CO_2$ sequestration storage capacity and may have a significant impact on the country's Just Transition.

**Significance:**

This study shows that basaltic sequences may support the permanent storage of anthropogenic $CO_2$ in South Africa, in particular, proximal to significant point-source $CO_2$ emitters. South Africa has voluminous and widespread basaltic sequences, which, in combination, increase South Africa's geological $CO_2$ storage potential by several orders of magnitude. These storage reservoirs can have a direct impact in South Africa by enabling a sustainable Just Transition toward a low-carbon economy while meeting intended climate change mitigation scenarios.

## Introduction

South Africa is the leading $CO_2$ emitter on the African continent and has one of the largest rates of $CO_2$ emissions in the world.[1] These emissions largely stem from the nation's heavy reliance on coal as a primary energy-generation feedstock.[2] South Africa has extensive geological sedimentary basins that contribute toward proven reserves of at least 30 billion tonnes of coal. This makes South Africa one of the largest coal producers globally.[3] South Africa has used these coal resources to effectively impact the country's industrialisation and socio-economic development. The coal industry employs at least 100 000 people and contributes a third of mining's total contribution to the country's GDP.[4] However, the South African government has underscored the need to combat climate change and has a target of reducing $CO_2$ emissions by at least 50% within the next 10 years (Figure 1).[5] It aims to do this through a drastic reduction in coal-fired energy and shifting toward alternative forms of energy.[6] However, with coal forming such a critical role in South Africa's socio-economic and energy landscape, this shift cannot be immediate and requires a careful Just Transition, i.e. a transition that will enable South Africa's intended climate change mitigation strategies while limiting potential negative socio-economic effects associated with the coal and linked industries.[7] Balancing South Africa's coal industry and climate change mitigation will therefore require the implementation of innovative and novel technologies, such as carbon capture, utilisation and storage.[8]

Carbon capture, utilisation and storage (CCUS) technologies aim to reduce atmospheric $CO_2$ emissions by capturing $CO_2$ at the source (e.g. point-source emitters such as coal-fired plants), and transporting and storing the captured $CO_2$ in underground storage reservoirs. Some of the captured $CO_2$ may be used in additional downstream industries, e.g. various petrochemical processes.[9] CCUS investigations in South Africa have typically looked at deep saline aquifers, relatively deep coal seams, and depleted oil and gas fields as potential storage reservoirs. In combination, these amount to approximately 150 gigatons of potential $CO_2$ storage, with much of this potential (98%) located within offshore volcano-sedimentary basins.[10] Critically, these large potential storage reservoirs are far removed from South Africa's coalfields and $CO_2$ emission hotspots. In general, South Africa's coal reserves, current coal utilisation and subsequently most $CO_2$ emissions occur in the northeast of the country.[4] If South Africa is to enable a successful Just Transition, potential $CO_2$ storage reservoirs proximal to these coalfields and emission hotspots must be investigated and developed.

Basaltic rocks – that is, rocks rich in iron, calcium, magnesium, and aluminium silicate minerals – are regarded as very promising $CO_2$ storage reservoirs.[11-13] This is largely because basaltic rocks are globally voluminous[14]; have unique trapping mechanisms linked to their multi-phase geodynamic emplacement[15]; and have a chemical composition that is highly susceptible for mineral carbonation on a large scale and which is several orders of magnitude faster than in classical siliciclastic reservoirs[16]. South Africa has extensive basaltic occurrences across the country[17]; however, these have not been investigated as potential $CO_2$ storage reservoirs. We present the findings of geological and mineralogical analyses conducted on Ventersdorp Supergroup samples collected from boreholes proximal to major point-source $CO_2$ emitters and discuss the implications for support of larger-scale $CO_2$ sequestration.

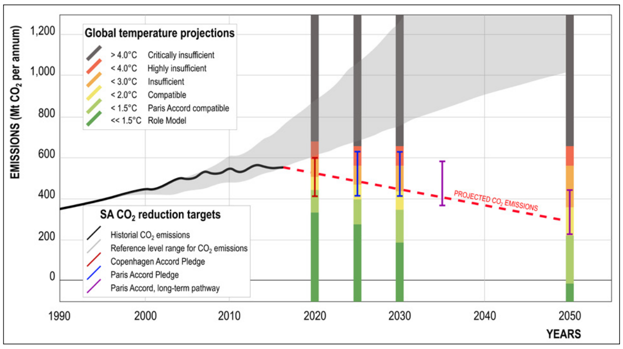


**Figure 1:** Projected $CO_2$ emissions for South Africa, as per climate change mitigation scenarios. Overall global temperature rise predictions are also presented.[18]

## Onshore geological $CO_2$ storage in South Africa

Several critical geological conditions must be met when defining a safe and permanent prospective onshore $CO_2$ storage reservoir. These conditions include the existence of an appropriately thick geological sequence that is adequately permeable and porous to enable the injection and controlled movement of $CO_2$-bearing fluids throughout the target reservoir. The reservoir should consist of components that are naturally amenable to reacting with the injected $CO_2$. This reactivity is critical to ensure that the injected $CO_2$ converts to a solid form and is permanently stored. Geological sequences should also be relatively homogeneous across the targeted reservoir to accommodate a large volume of injected $CO_2$. The targeted reservoir should be under- and overlain by adequately thick impermeable and non-porous geological sequences. These sequences will act as reservoir seals to restrict the movement and possible escape of the injected $CO_2$. The region should be relatively tectonically undeformed. This would limit the presence of seismicity and geological structures that may promote undue movement of the injected $CO_2$.[19] Environmental baseline investigations are critical. The target region requires an extensive and accurate assessment of the natural conditions, including understanding the biosphere, hydrosphere, and pedosphere. This information is needed to monitor any potential deviation from natural conditions during and after the injection of $CO_2$. Once injected, the $CO_2$ can be stored either within the reservoir pore and/or mineral spaces, various geological structures or within saline fluids present at the injected depth. The injected $CO_2$ might react with reservoir lithologies and in-situ fluids and be converted to carbonate minerals.[20] Conversion to carbonate minerals is ideal because the $CO_2$ is rendered immobile and is permanently stored. Globally, the vast majority of current CCUS projects target storage of $CO_2$ in deep saline aquifers with a significant proportion of the captured $CO_2$ utilised to enhance oil and gas recovery.[9] Furthermore, research into South Africa's potential onshore $CO_2$ storage reservoirs has largely focused on conventional deep saline aquifer storage in relatively young (i.e. Palaeozoic and younger) sedimentary sequences.[21,22] Much of these sequences are located along the near-shore and offshore along the South African coastline.[10,23] Consideration of basaltic rocks as a potential $CO_2$ reservoir is relatively new.[11] Basaltic reservoirs are promising because the mineralogy of basaltic rocks is most amenable to support injected $CO_2$ being converted to carbonate minerals. Basaltic rocks have minerology that is rich in iron, calcium, magnesium, and aluminium. These react readily with $CO_2$ and produce carbonate minerals such as calcite, dolomite, and ankerite.[24,25] Furthermore, mineral carbonation in basaltic rocks occurs several orders of magnitude faster than in conventional siliciclastic reservoirs.[11,12] While South Africa does have extensive basaltic sequences, these have not been considered as potential $CO_2$ storage reservoirs.

## The Ventersdorp Supergroup

The Ventersdorp Supergroup is one of the largest and oldest volcano-sedimentary successions on earth. These successions are largely located in the northern part of South Africa, including proximal to the large coalfields and major point-source $CO_2$ emitters (Figure 2). This makes it a viable option for further investigation as a potential basaltic $CO_2$ reservoir.

Vast sequences of mafic to ultramafic volcanic rocks interspersed with felsic and siliciclastic sequences dominate the Ventersdorp Supergroup (Figure 3). These rocks were emplaced as a Large Igneous Province during Mesoarchean intraplate tectonic activity atop the Kaapvaal Craton.[26] The various volcanic assemblages cover a surface area of more than 200 000 km$^2$ and attain a thickness of more than 5 km.[27]

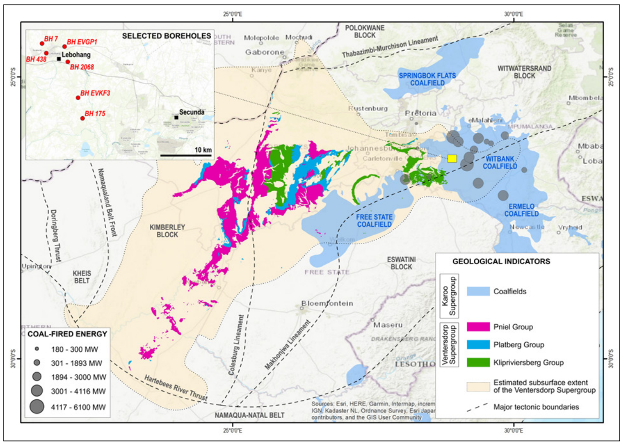


**Figure 2:** Overview of the extent of the Ventersdorp Supergroup. Included are the positions of the major point-source $CO_2$ emitters and their associated coalfields. Inset shows locations of geological boreholes used in this study. Data from the Council for Geoscience Data Portal.[28]

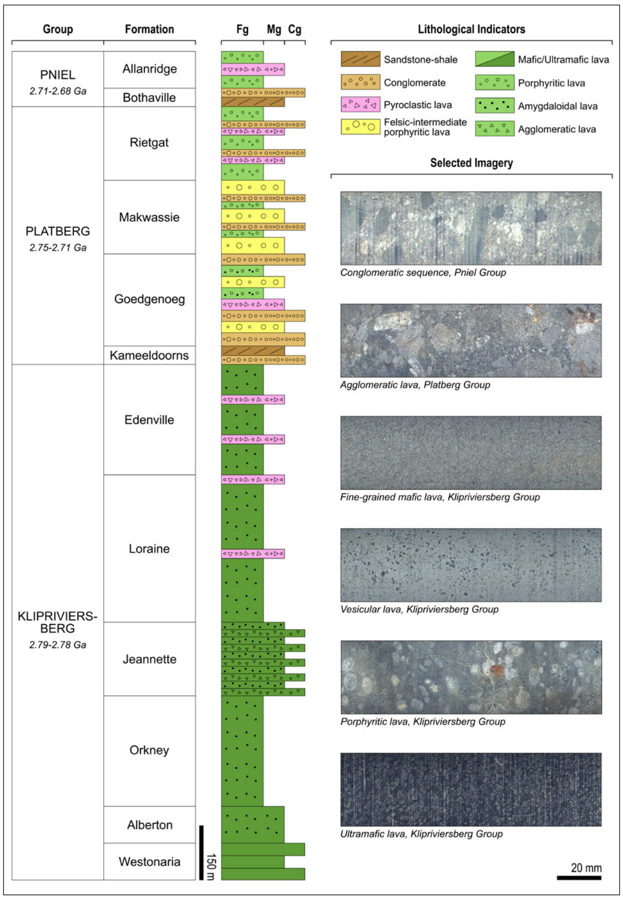


**Figure 3:** Generalised stratigraphic column of the Ventersdorp Supergroup. Fg, Mg and Cg refers to fine-grained, medium-grained and coarse-grained, respectively. Geological information gathered from various sources.[26,29,36-38] Images from samples at the Council for Geoscience National Core Library.[28]

Stratigraphically, the lowermost part of the Ventersdorp Supergroup is defined by ca 2 km thick continental flood basalt assemblage of the ca 2791–2779 Ma Klipriviersberg Group.[29] This comprises a wide range of volcanic rocks including fine-coarse grained mafic and ultramafic sequences, agglomerates, and vesicular porphyritic lavas. The lowermost part of the Klipriviersberg Group comprises ultramafic komatiitic-type lavas of the Westonaria Formation. The overlying Alberton Formation is characterised by the presence of large (2–10 cm) plagioclase phenocrysts. Overlying the Alberton Formation are homogeneous ultramafic lavas and several interlayered tuff beds. The occurrence of multiple agglomerate layers denotes the Jeanette Formation with a transition to very-fine-grained lavas with distinctive spherule beds highlighting the Loraine Formation. The Edenville Formation defines the uppermost sequence of the Klipriviersberg Group and is characterised by green chalcedony and white quartz amygdales. Overlying the Klipriviersberg Group are ca 2 –km-thick interlayered basin-fill high-energy siliciclastic and mafic-ultramafic volcanic sequences of the ca 2754–2709 Ma Platberg Group.[29] This begins with a lowermost sequence of conglomerate and coarse-grained sandstone of the Kameeldoorns Formation. Overlying the Kameeldoorns is a series of andesitic porphyritic lavas of the Goedgenoeg Formation. A sequence of quartz-feldspar porphyries defines the overlying Makwassie Formation. The uppermost sequence of the Platberg Group is characterised by mafic volcanic rocks interlayered siliciclastic and chemical sedimentary rocks. A series of ca 1-km thick siliciclastic and more felsic volcanic rocks comprises the uppermost ca 2720 Ma Pniel Group.[30] The lowermost sequence is defined by the Bothaville Formation and consists of varied siliciclastic layers, including arenaceous and conglomeratic units interlayered with tuffs. The uppermost sequence consists of amygdaloidal basalts of the Allanridge Formation.

The sequences of the Ventersdorp Supergroup are relatively undeformed and were subjected to low-mid grades of greenschist facies metamorphism, as inferred from the underlying Witwatersrand and overlying Transvaal Supergroups.[31] Brittle structures and associated vertical and lateral offset are recorded.[32] These structures are typically associated with deep crustal features, such as the Colesburg and Makhonjwa Lineaments (Figure 2). These structures formed during the amalgamation of the Kaapvaal Craton during the Neoarchean[33], and would have undergone several phases of convergent and extensional reactivation linked to continental cycles[34]. Importantly, these structures also form critical zones that enabled stress accumulation and the development of proximal structures where much of the regional deformation would be exhibited.[35]

## Evaluating a potential reservoir in the Ventersdorp Supergroup

Several important considerations are needed for the sequences of the Ventersdorp Supergroup to be considered as a potential $CO_2$ storage reservoir. These considerations include determining if these sequences are adequately thick and laterally extensive and whether there is an appropriate amount of stratigraphic heterogeneity to enable the development of reservoir and corresponding seal lithologies. Furthermore, these potential sequences should be relatively devoid of certain kinds of regional structures that may enable the possible escape and/or migration of injected $CO_2$ and possible undue interaction with other natural systems, e.g. groundwater aquifers. To enable these estimations, several boreholes with a depth range of ca 1000–2000 m were considered in this study (Table 1; Figure 2). These were logged and scanned with a SisuROCK hyperspectral core scanner at the Council for Geoscience National Core Library. Selected samples were also collected along some of the boreholes for various petrographic and mineralogical analyses (Figure 2; Figure 4).

**Table 1:** Overview of selected boreholes considered in this study. Data from the Council for Geoscience National Core Library.[28]

| Borehole ID | Latitude | Longitude | Date drilled | Depth |
|---|---|---|---|---|
| BH 7 | -26,3622 | 28,9004 | March 1936 | 1501 m |
| BH 438 | -26,3766 | 28,8937 | November 1964 | 1019 m |
| BH EVGP 1 | -26,3666 | 28,9473 | June 1987 | 2094 m |
| BH 2068 | -26,3936 | 28,9542 | January 1989 | 1994 m |
| BH EVKF 3 | -26,4647 | 28,9761 | October 1988 | 1606 m |
| BH 175 | -26,5025 | 28,9842 | January 1956 | 1205 m |

### *Hyperspectral borehole scanning*

Selected geological boreholes were used to develop a ca 20-km long geological profile and to ascertain the subsurface extent of the Ventersdorp Supergroup sequences proximal to South Africa's significant point-source $CO_2$ emitters (Figure 2). Furthermore, high-resolution mineral spectral information was gathered from the selected boreholes through hyperspectral borehole scanning. Hyperspectral scanning of the boreholes enables reflectance spectroscopy to be undertaken across different spectral regions, including the visible-near infrared, short-wave infrared, and long-wave infrared. The spectral absorption characteristics of various elements enables the identification of mineralogy and their associated textures. Spectral processing includes the development of dominant mineral maps and various mineral indices. This includes high band ratio ranges of mean depth and wavelength spectral signatures in the long-wave infrared, which specifically responds to the occurrence of mafic silicate minerals, i.e. those critical to support potential reactivity with $CO_2$. In addition, albedo reflectance was also considered. This denotes regions with higher concentration of felsic mineralogy. This information combines to provide critical subsurface delineation of the geology and dominant mineralogy. Borehole BH 2068 was considered and scanned as a reference borehole. The results are shown in Figure 5.

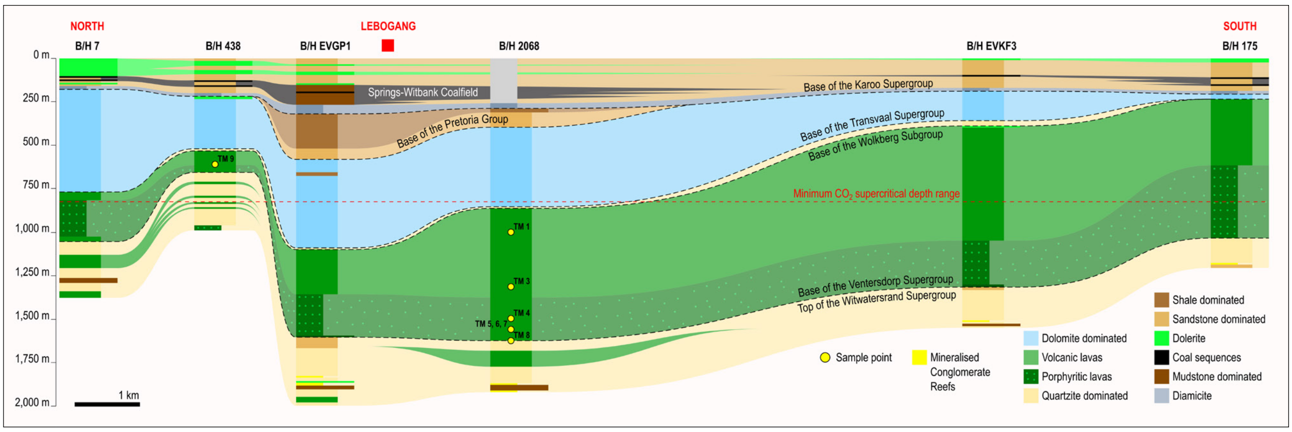


**Figure 4:** Schematic geological profile developed proximal to South Africa's significant point-source $CO_2$ emitters, as shown in Figure 2. Data from the Council for Geoscience Data Portal.[28]

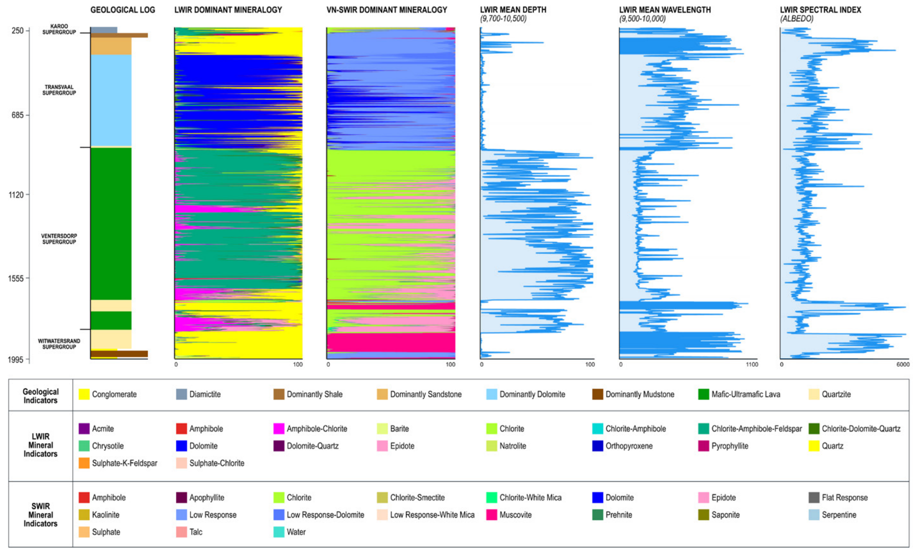


**Figure 5:** Overview of hyperspectral data acquired on borehole BH 2068. Figure includes simplified geological log; dominant mineral map from the visible-near infrared to long-wave infrared; long-wave infrared mean depth ranges, wavelength, and spectral index.

| NOTABLE SAMPLE CHARACTERISTICS | |
|---|---|
| **Sample** | TM 1 |
| **Lithology** | Ferroaxinite vein |
| **Dominant mineralogy** | Ferroaxinite (70 %); Quartz (20 %); Clinopyroxene (5 %) |
| **Texture** | Fine grained |
| **Pore space (%)** | c. 5 % |
| **Alteration** | < 1 % |
| **Carbonation** | < 1 % |
| **Sample** | TM 2 |
| **Lithology** | Amygdaloidal basalt |
| **Dominant mineralogy** | Plagioclase (30 %); Clinopyroxene (15 %); Chlorite (15 %) |
| **Texture** | Fine to medium grained |
| **Pore space (%)** | c. 13 % |
| **Alteration** | c. 20 % |
| **Carbonation** | < 1 % |
| **Sample** | TM 3 |
| **Lithology** | Basalt |
| **Dominant mineralogy** | Quartz (50 %); Epidote (45 %); Calcite (1 %) |
| **Texture** | Medium grained |
| **Pore space (%)** | c. 2 % |
| **Alteration** | c. 45 % |
| **Carbonation** | < 1 % |
| **Sample** | TM 4 |
| **Lithology** | Basalt |
| **Dominant mineralogy** | Clinopyroxene (20 %); Plagioclase (20 %); Chlorite (15 %) |
| **Texture** | Fine grained |
| **Pore space (%)** | c. 12 % |
| **Alteration** | c. 20 % |
| **Carbonation** | < 1 % |
| **Sample** | TM 5 |
| **Lithology** | Basalt |
| **Dominant mineralogy** | Clinopyroxene (25 %); Plagioclase (15 %); Chlorite (20 %) |
| **Texture** | Medium to coarse grained |
| **Pore space (%)** | c. 14 % |
| **Alteration** | c. 20 % |
| **Carbonation** | < 1 % |
| **Sample** | TM 6 |
| **Lithology** | Basalt |
| **Dominant mineralogy** | Clinopyroxene (20 %); Chlorite (20 %); Epidote (20 %) |
| **Texture** | Coarse grained |
| **Pore space (%)** | c. 13 % |
| **Alteration** | c. 40 % |
| **Carbonation** | < 1 % |
| **Sample** | TM 7 |
| **Lithology** | Amygdaloidal basalt |
| **Dominant mineralogy** | Clinopyroxene (50 %); Chlorite (20 %); Epidote (15 %) |
| **Texture** | Fine to medium grained |
| **Pore space (%)** | c. 10 % |
| **Alteration** | c. 35 % |
| **Carbonation** | c. 10 % |
| **Sample** | TM 8 |
| **Lithology** | Ultramafic basalt |
| **Dominant mineralogy** | Talc (50 %); Epidote (30 %); Hematite (10 %) |
| **Texture** | Coarse grained |
| **Pore space (%)** | c. 5 % |
| **Alteration** | c. 80 % |
| **Carbonation** | c. 50 % |
| **Sample** | TM 9 |
| **Lithology** | Porphyritic basalt |
| **Dominant mineralogy** | Calcite (50 %); Chlorite (25 %); Quartz (15 %) |
| **Texture** | Coarse grained |
| **Pore space (%)** | c. 10 % |
| **Alteration** | c. 75 % |
| **Carbonation** | c. 50 % |

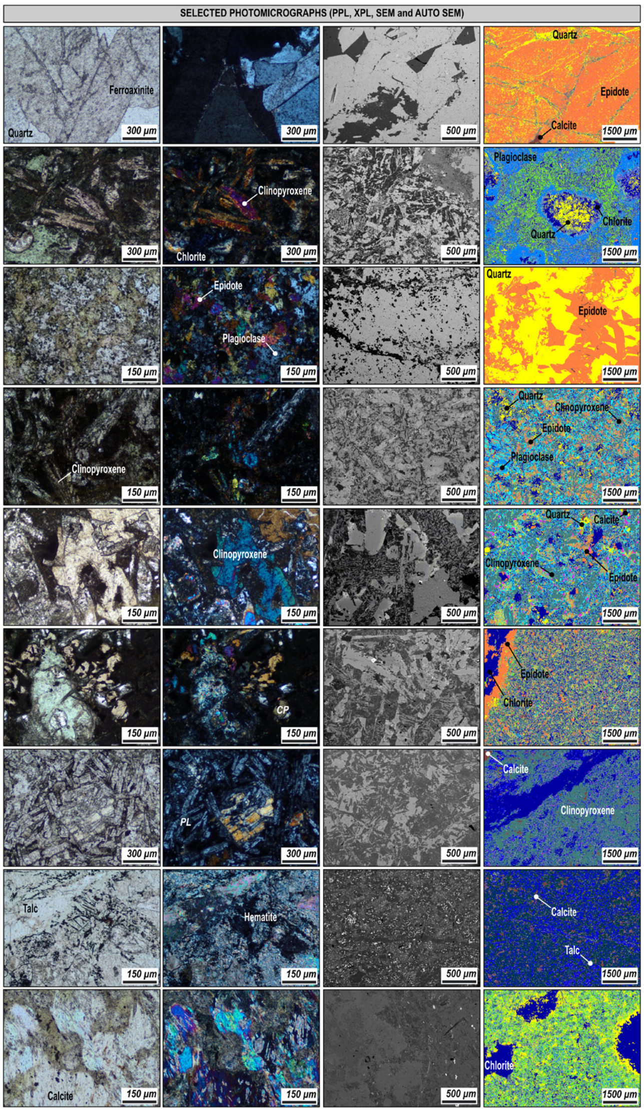


**Figure 6:** Overview of petrographic analyses and photomicrographs of samples of the Ventersdorp Supergroup sequences. Photomicrographs include optical microscopy in plane polarised light (PPL), cross-polarised light (XPL), and automated (Auto SEM) and scanning electron microscopy (SEM). Information is also provided on characteristic features.

### *Petrography*

Petrographic analyses were undertaken on selected samples of sequences of the Ventersdorp Supergroup (Figure 6). This analysis was conducted to test their characteristics and potential as possible $CO_2$ storage sequences. Petrographic analyses were conducted in both transmission light microscopy and automated scanning electron microscopy with energy dispersive x-ray spectrometry. These analyses enable the development of micron-scale compositional and mineral maps of the samples collected. The large depth of field range and magnification enables robust characterisation of pore space size and quantification. Quantification of the elements present allows for a more accurate mineral classification based on the stoichiometry to produce a fully quantified and detailed mineral map. This also enables the identification and quantification of the mafic and alteration minerals, including any natural carbonation. In this study, carbon-coated sample mounts were analysed using a Carl Zeiss Sigma 300 VP FEG-SEM with an energy dispersive x-ray spectroscopy and backscatter electron detector.

## Results

### *Subsurface geology*

The geological profile suggests extensive occurrences of the Karoo, Transvaal, Ventersdorp and Witwatersrand Supergroups across the study area. Sequences of the Karoo Supergroup are generally homogeneous in thickness and extent across the study area. The topmost sequences of the Transvaal Supergroup are also correlative across the study area; however, there is significant heterogeneity along the basal part. There is also a notable thinning of the Transvaal Supergroup toward the south. The Ventersdorp and underlying Witwatersrand Supergroups are also generally well correlated across the study area. However, there is a significant thinning and thickening of these sequences toward the south and north, respectively. Stratigraphically, the boreholes suggest that, generally, only the lower part of the Ventersdorp Supergroup is preserved around the study area, i.e. sequences of the Klipriviersberg Group, while sequences of the Platberg and Pniel groups are poorly preserved.

The subsurface geological profile is well supported by the hyperspectral borehole scanning. The significant changes across the various supergroups are well delineated through the different spectral signatures. Spectral signatures suggest distinctive zones with high concentrations of mafic silicate minerals throughout the Ventersdorp Supergroup sequence. Furthermore, it also highlights zones with higher felsic mineralogy. Importantly, the hyperspectral signatures also provide constraints on the degree of alteration. The results suggest that alteration of the Ventersdorp Supergroup lavas increases toward the very base of the sequence, with appreciable signatures of metasomatic and hydrothermal minerals along the contact zone with the underlying Witwatersrand Supergroup.

### *Mineralogy*

The results of the petrographic analyses correspond well to the reported lithodemic sequences of the lower part of the Ventersdorp Supergroup.[26,29,36-38] Lithologies underlying the study area are largely comprised of mafic to ultramafic basaltic sequences that vary between fine-grained lavas to coarser porphyritic and amygdaloidal sequences. In general, the volume of mafic minerals and coarsening of texture increases toward the base of the sequence. There is also a correlation between the estimated pore space and the texture, with the coarser-grained sequences highlighting relatively increased pore space. The presence of secondary minerals such as chlorite, epidote, and calcite highlights hydrothermal and metasomatic alteration. In general, alteration is relatively minimal with an increase toward the base of the sequence. Importantly, where alteration is low, iron-, magnesium-, and calcium-rich silicate minerals (i.e. euhedral pyroxenes) are still preserved.

## Conclusion and implications for South Africa's Just Transition

Enabling a successful Just Transition in South Africa is not straightforward. Currently, South Africa has a very strong reliance on coal, although the country is targeting significant reductions in $CO_2$ emissions. The successful implementation of CCUS technologies is crucial to support the Just Transition and a shift toward a low-carbon economy. Existing CCUS studies in South Africa suggest limited onshore $CO_2$ storage potential, with much of this restricted to relatively young volcano-sedimentary sequences that are far removed from South Africa's significant $CO_2$ emitters and coalfields.[10,23] Basaltic sequences are showing promise as additional $CO_2$ storage reservoirs. This is crucial because basaltic sequences are globally extensive and have mineralogy that is highly reactive and may rapidly enable the mineralisation of injected $CO_2$ into an array of carbonate minerals.[11-13]

In this study, we considered the volcanic sequences of the Ventersdorp Supergroup as a potential storage reservoir of anthropogenic $CO_2$. The known extent of the Ventersdorp Supergroup has been increased from ca 200 000 km$^2$ [38] to at least 280 000 km$^2$. Importantly, the additional surface area extends beneath South Africa's highly developed coalfields and largest point-source $CO_2$ emitters (Figure 2). Moreover, subsurface geological profiles highlight volcanic sequences that are adequately thick and at depths appropriate to support potential $CO_2$ storage. Furthermore, hyperspectral information suggests that these sequences are adequately heterogeneous in developing layers of potential reservoir and accompanying sealing lithologies (Figure 5). The volcanic sequences thin significantly north of the study area (Figure 4). This thinning is likely due to the presence of underlying structural and geological controls. This possibly forms a significant structural trap for the storage of $CO_2$, but also suggests that any potential development of CCUS targeting the Ventersdorp Supergroup cannot extend further north from the study area.

Despite these lavas being emplaced during the Archean, alteration is limited and not widespread throughout the sequence (Figure 6). Metasomatic alteration and carbonation of reactive minerals (e.g. iron-, calcium-, magnesium-, and aluminium-rich silicates) occurs toward the base of the sequence, near the contact zone with the underlying Witwatersrand Supergroup. This is likely linked to the occurrence of the Ventersdorp Contact Reef, forming the boundary zone between the Ventersdorp Supergroup and the underlying Witwatersrand Supergroup. In general, more coarse-grained porphyritic lavas have relatively higher porosity estimates (i.e. ideally ranging between ca 15% and 30%) that could support the uptake of injected $CO_2$.[39]

South Africa has an extensive geological evolution that saw the emplacement of several Large Igneous Provinces (Figure 7). This includes extensive basaltic sequences emplaced within the Makhonjwa (Barberton) Supergroup[40]; Pongola Supergroup[41]; Transvaal Supergroup and Bushveld Complex[42,43]; Soutpansberg Group[44]; and Karoo Supergroup[45]. These various sequences cover a significantly large surface area and should be further investigated. This would have a significant bearing on potential onshore CCUS sites in South Africa, in particular, by increasing the known geological anthropogenic $CO_2$ storage reservoirs by several orders of magnitude.

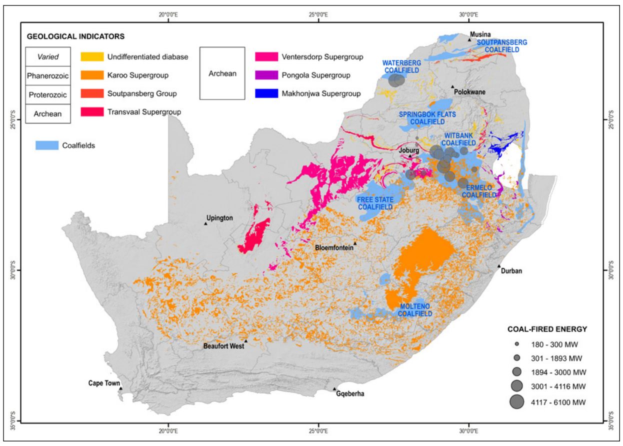


**Figure 7:** Overview of surface expression of significant basaltic sequences across South Africa together with coalfields and coal-fired energy generation plants. Data from the Council for Geoscience Data Portal.[28]

Before geological storage of $CO_2$ in basaltic sequences can occur, several aspects need to be addressed and further investigated:

- The subsurface extent of these sequences needs to be adequately delineated (Figure 7). This process includes establishing the lithodemic variations, inclusive of mineralogy, texture, and various degrees of alteration. This information is pertinent toward attaining precise volumetric estimations of potential basaltic $CO_2$ storage and their occurrence relative to other geological sequences of interest, e.g. those hosting various mineral occurrences, and the geographic location relative to present and predicted future $CO_2$ emission sources.
- A consolidation of legacy and new baseline data is needed. This includes attaining an adequate understanding of the natural conditions around prospective $CO_2$ storage sites, especially proximal to regions that have been subject to long-standing mining and exploration activities. This kind of information will also assist in developing tangible $CO_2$ utilisation considerations that may contribute toward environmental remediation.
- Implications for enabling a sustainable and inclusive Just Transition need to be determined. Global development and advancement of CCUS technologies are increasing. With the inclusion of basaltic storage, global volumetric $CO_2$ storage potential will significantly increase. This will need to be considered within the context of the Just Transition toward a low-carbon economy, especially in developing countries that are heavily reliant on fossil fuels, especially hydrocarbons. These considerations should be used to develop/revise current long-term sustainable energy development strategies, in particular those linked to carbon-reduction measures, e.g. carbon taxing.[46]

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## Competing interests

We have no competing interests to declare.

## Authors' contributions

T.D.: Conceptualisation; methodology; data collection; data analysis; validation; writing – initial draft; writing – revisions; project leadership; project management. T.Ma., M.T., Z.S., V.N., P.M., T.Mu., C.N., N.H.: Methodology; data collection; sample analysis; writing – initial draft; writing – revisions. M.Sc., N.M., N.Z., T.Mo., M.Sa.: Data collection; data curation; writing – revisions.

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# *Monilinia fructicola* intercepted on *Prunus* spp. imported from Spain into South Africa between 2010 and 2020

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The international trade of plants and their products, such as fresh fruits, can facilitate the introduction and spread of foreign pests and diseases. We examined South Africa's import of stone fruits (*Prunus* spp.) as a pathway for introducing *Monilinia fructicola* (G. Wint.) Honey and document recommended phytosanitary measures to deal with the risk associated with its exportation into the country. Fresh fruits of *Prunus* spp. are imported from various countries. The current study provides a report on 10 years (2010–2020) importation of *Prunus* spp. from Spain to South Africa with associated cases of *M. fructicola.* We also detail the current management measures for imported stone fruits from Spain to South Africa. We report 18 *M. fructicola* detections that were found during the study period. The number of detections presents enough trends to determine the level of phytosanitary concerns regarding the importation of *Prunus* spp. fresh fruit from Spain, which cannot be neglected. *M. fructicola* is an economically important brown rot on many fruit hosts and potentially threatens agricultural and horticultural industries, the environment, and biodiversity in South Africa. The importation of *Prunus* spp. requires intensive management strategies for *M. fructicola,* as pathogens may pose a major phytosanitary concern because it could thrive and reproduce in various environmental conditions and on various host plants in South Africa. Therefore, if *M. fructicola* establishes in South Africa, its impacts will have consequences for different key socio-economic sectors, including the agricultural industry.

**Significance:**

- *Monilinia fructicola* is a pest of quarantine significance for South Africa.
- If not managed properly, the importation of *Prunus* spp. with associated *M. fructicola* will be a significant phytosanitary concern that could cause severe economic impacts on the South African agricultural industry.

## Introduction

International movement of plant products such as fresh fruits through trade is a pathway by which foreign pests can be transported and introduced to new areas. Plant pests are known to affect infrastructure, agriculture, and biodiversity negatively.[1] Due to climate change and variability, the impacts associated with invasive pests are likely to increase steadily, leading to more stringent trade restrictions and border inspection rates by trading partners.[2] Moreover, challenges are perceived when the pests are detected in countries that largely depend on economic structure, such as agricultural exports and other industries and ecosystems.[3]

One of the most economically important pests of *Prunus* spp. is *Monilinia* spp., which results in blossom blight and brown fruit rot.[4,5] Amongst the various variants of brown rot, *Monilinia fructicola* (G. Wint.) Honey is regarded as the most destructive disease host plant belonging to subfamilies Prunoideae and Pomoideae globally.[6-8] However, this pest is more common on ripening stone fruits and less common on pome fruits.[9-11] Its direct economic impact is through destroying and/or significantly reducing a crop yield at pre-and post-harvest stages by eliminating blossoms or rotting mature fruits.[12] The disease also infests the leaves and shoots of host plants.[13] Importing fresh fruit poses a prospective risk to local host plants through extremely dispersible, abundant spores of *M. fructicola* from reused packaging and disposal sites for discarded fruit.[14] *M. fructicola* subsists on mummified fruits.[15,16] The yellowish exogenous stromata display the principal symptom on peaches, pears, and apples approximately 15 days after ripening.[15,17]

The impact of *M. laxa* and *M. fructigena* on fruits is considered minimal compared to that of *M. fructicola.*[16] Studies have indicated that the latter pest is more aggressive and hard to control due to its anastomosis behaviour and sexual recombination.[18] It is also known to contain a tremendous genetic change, making and possessing a higher potential to overcome genetic barriers.[19-24] Of all the stone fruits' pests, *M. fructicola* is also considered the most highly transmissible pest known to infect the plants at different growth stages, including flowers, twigs, and fruits.[19-22]

Over the past 70 years, trade disputes have been raised concerning the classification pertaining to the official status of the presence of *M. fructicola* in South Africa. Currently, the National Plant Protection Organisation of South Africa lists *M. fructicola* as a quarantine pest for South Africa on phytosanitary import requirements of fresh fruits and propagation materials for *Prunus* spp., *Pyrus* spp., *Cydonia* spp., *Malus* spp. and *Vitis* spp. The International Plant Protection Convention (IPPC) defines pests as 'any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products'[25]. It further defines quarantine pests as 'a pest of potential economic importance to the area endangered thereby and not yet present there, or present but not widely distributed and being officially controlled'. *M. fructicola* is not known to occur in South Africa, although it was mistakenly declared.[26-32]

The introduction of *M. fructicola* into South Africa could have an undesirable impact on the country's stone and pome fruit production. Stone fruit production in South Africa is the largest in Africa, accounting for 16% of southern hemisphere output and 1% of global production.[31] Of the stone fruit produced in South Africa, 20% is exported and the rest is locally consumed. The value of the stone fruit industry in South Africa is ZAR2 billion annually. South Africa produces about 1.3 million tonnes of apples and pears per year.[31] The value of the pome fruit industry in South Africa is ZAR8 billion annually. We aimed to provide a report on a 10-year period (2010–2020) of importation of *Prunus* spp. from Spain to South Africa with associated cases of *M. fructicola* and to recommend additional phytosanitary measures to deal with the risk associated with its exportation in South Africa.

## Material and methods

### *Data collection*

The data in the current study were obtained from 702 samples from the imported consignments of fresh fruit of *Prunus* spp. from Spain to South Africa, based on convenience sampling (also known as haphazard sampling or accidental sampling). These samples were collected from three ports of entry in South Africa: (1) OR Tambo International Airport, (2) Cape Town, and (3) Port Elizabeth Harbour. Consignments were inspected by the quarantine inspectors from the Department of Agriculture, Land Reform and Rural Development (DALRRD) between 2010 and 2020, to determine if pests were present and/or to determine compliance with phytosanitary regulations. International Standard for Phytosanitary Measures (ISPM) No. 31 describes procedures for inspecting consignments of plants, plant products and other regulated articles at import and export.[33] It is focused on determining compliance with phytosanitary regulations, based on visual examination, documentary checks, and identity and integrity checks. A confidence level of 95% is commonly used during inspection and sampling.[34] A 95% confidence level means that the conclusions drawn from the sampling results will detect a non-compliant consignment, on average, 95 times out of 100. Therefore, it may be assumed that, on average, 5% of non-compliant consignments will not be detected. If the inspector has grounds to believe that the consignment contains brown rot, a sample will be extracted and sent to the DALRRD laboratory for additional examination and identification. All fruits suspected to be infested with brown rot were collected and identified using the diagnostic protocol for *Monilinia* species.[35-37]

### *Data analysis*

Records of *M. fructicola* interceptions on *Prunus* spp. between 2010 and 2020 were examined. The number of *Prunus* spp. samples and *M. fructicola* interception frequencies were recorded. Data on *M. fructicola* were evaluated according to the number of samples inspected, year, and number of cases (both positive and negative) recorded. Risk ratings and scores of intercepted *M. fructicola* from the imported *Prunus* spp. fresh fruit were generated based on ISPM Numbers 2 and 11, as well as the guidelines of the US Animal and Plant Health Inspection Service – Plant Protection and Quarantine.[37-39]

## Results and discussion

### Monilinia fructicola *interception via fruit imports*

We aimed to report on 10 years' of importation of *Prunus* spp. to South Africa from Spain and their associated cases of *M. fructicola.* The introduction of *M. fructicola* into South Africa could negatively impact stone and pome fruit production in the country. Over a period of 10 years, we recorded 18 *M. fructicola* detections across the three ports of entry investigated. The highest number of *M. fructicola* interceptions were recorded between 2010 and 2015 (Table 1). The highest numbers of samples sent for laboratory analysis to determine infestation with *M. fructicola* was in 2014 (97), 2015 (136) and 2016 (113). The least number of samples sent for inspection was in 2011 and 2020. There was no interception of *M. fructicola* on the samples inspected in 2011, 2016, 2017, 2018 and 2020 (Table 1).

*M. fructicola* has been reported in various countries around the globe. However, unless extra phytosanitary measures are taken in South Africa, transmission to local orchard trees through highly dispersible, profuse spores from recycled packaging materials and fruit disposal sites may not necessarily happen.[40] In Spain, the first report of *M. fructicola* on plums was recorded in the southwestern part of the country.[41] During that period *M. fructicola* was a quarantined pathogen in Europe and was reported on imported apricot, nectarine and peach in several European countries.[41]

**Table 1:** Number of *Prunus* spp. fresh fruit imported from Spain and number of interceptions of *Monilinia fructicola* through OR Tambo International Airport, Cape Town Harbour, Cape Town International Airport and Port Elizabeth Harbour between 2010 and 2020.

| Year | Number of samples inspected for *M. fructicola* | Number of negative cases | Number of positive cases |
|---|---|---|---|
| 2010 | 74 | 65 | 9 |
| 2011 | 25 | 25 | 0 |
| 2012 | 41 | 40 | 1 |
| 2013 | 50 | 48 | 2 |
| 2014 | 99 | 97 | 2 |
| 2015 | 136 | 133 | 3 |
| 2016 | 113 | 113 | 0 |
| 2017 | 59 | 59 | 0 |
| 2018 | 39 | 39 | 0 |
| 2019 | 47 | 46 | 1 |
| 2020 | 19 | 19 | 0 |
| **Total** | **702** | **684** | **18** |

*M. fructicola* was discovered on imported peaches from Italy and Spain in a produce market and other stores in Budapest (Hungary) in early October 2005.[14] *M. fructicola* was first discovered in stores on imported fruit in Switzerland, causing brown rot symptoms identical to those produced by indigenous *M. fructigena* and *M. laxa.*[14] During the survey conducted by Bosshard et al.[14], *M. fructicola* was found on all imported apricots and nectarines from the USA and France in imported fruit market. In Czech Republic, 56 samples were tested for the presence of *Monilinia* spp. during a survey conducted in the summer of 2006. *M. fructicola* was found in 15 samples from 11 different locations around the country, mostly on peaches, apples, and sweet and sour cherries.[42]

Interestingly, in the current study reporting on 255 samples of *Prunus* spp. fresh fruit samples processed in 2011, 2016, 2017, 2018 and 2020, there was no interception of *M. fructicola*. However, in 2010, when only 74 samples were inspected, there were 9 reported cases of *M. fructicola*.

The number of detections presents enough trends to determine the level of phytosanitary risk associated with the importation of *Prunus* spp. fresh fruit from Spain. Brown rot has been officially recognised in orchards in Austria, Spain, Czech Republic, Italy, and Germany since it was initially discovered in French orchards in 2001. In Switzerland, *M. fructicola* has also been reported on imported fruit in Hungary and Switzerland.[43] Peaches with brown rot were discovered in a 5-year-old orchard in Gorika, western Slovenia, in 2009. Fruit lesions and mummified fruits were among the symptoms.[44] Two imported peach isolates came from Greece and Spain, one nectarine isolate came from Greece, and the local plum isolate originated from Spisk tiavnik (Serbia).[45]

Brazil is an importer of stone fruits from Spain, Chile, the USA and Argentina. *M. fructicola* was originally detected in the nation due to imported stone fruit, and several isolates are able to adapt to the environment of Brazil's primary fruit producing regions. All *Monilinia* isolates studied were pathogenic to peaches, whereas isolates from Chile and the USA were able to induce brown rot in both wounded and unwounded apples and pears[46], presenting a high risk of *Monilinia* spp. in stone fruit production in Brazil.

In 2017, brown rot symptoms were seen on the fruit of Japanese apricot, peach, apricot, Japanese plum, and sweet cherry with 2–5% incidence levels in Korea.[47] This was the first confirmed report of brown rot caused by *M. fructicola*, resulting in early symptoms that eventually destroyed entire fruit crops in the country.[47]

*M. fructicola* is also a significant pest on *Malus* spp. (apples). In Italy, the first report of *M. fructicola* was recorded on apple.[48] In Mongolia, the highest interception rate of brown rot of apple fruit (37–41%) occurred in imported apples from China. About 12–19% of brown rot of apple was recorded in imported apples from the USA, while 11–29% was detected in imported apples from Russia.[49] This led to widespread brown rot through the imported apples.

Therefore, the South African apple industry also needs to be protected against invasion of *M. fructicola* through application of phytosanitary measures during import. In South Africa, the apple industry plays a significant role in the economy, considering their foreign exchange earnings, employment creation and linkages with support institutions.[50]

## *Economic consequences and recommended phytosanitary measures*

*M. fructicola* has been categorised as a quarantine pest based on its potential economic importance to the South African *Prunus* spp. fruit industry and it is currently not present in the country. *M. fructicola* is one of the most economically important diseases affecting stone and pome fruits in the orchards and after harvest by destroying or reducing a crop yield by killing blossoms or by rotting mature fruits.[5,51-56] Post-harvest losses of 80–85% may occur under favourable conditions for brown rot development.[16] In Indiana, the brown rot of apples was discovered on the fruit of 'pristine' apples, causing 50% crop loss in 2015.[57] Other apple growers reported a significant loss of 5–20%.[57] Among the species causing brown rot and blossom rot in the genus *Monilinia, M. fructicola* is regarded as the most highly infectious pathogen at different stages of plant growth.[21,23,24] It caused severe post-harvest yield losses, sometimes in excess of 30%, in California's Central Valley.[58]

Brown rot fungal infections can begin early in the growth season on blooms and/or young shoots.[16,59,60] While blossom blight outbreaks may not be severe enough to cause a serious decrease in fruit production, they still pose a risk.[59] At harvest, healthy fruit may be contaminated with spores, which then cause decay in storage and during marketing. Green fruits may harbour latent infections.[61] Fungi that infect such fruit remain dormant until the fruit begins to ripen.[62]

*M. fructicola* may be a major phytosanitary concern to the South African fruit industry because it could find favourable conditions for survival, development, reproduction and dispersal (Table 2). The importation of *Prunus* spp. from Spain should require intensive application of phytosanitary measures for *M. fructicola* both in export and port of entry through regular inspections. The environmental conditions in South Africa are diverse. Therefore, if *M. fructicola* is established in the country, impacts could lead to socio-economic consequences in various key agricultural sectors and biodiversity in general and loss of export markets by restricting trade by importing countries. This pest has never been reported on any of these plant species in South Africa, presenting a high risk if detected in the country through stone fruit import from Spain (Table 2).

South Africa is a major producer and exporter of *Prunus* spp. and pome fruits, which are major hosts of *M. fructicola*. As a consequence of introduction, this pest may pose a major restriction to trade by importing countries. Approximately 16% of the stone fruit grown in the southern hemisphere comes from South Africa.[32] About 20% of stone fruit produced in South Africa is for the export market, leaving the rest for local consumption. It is important to note that the value of the stone fruit industry in South Africa is ZAR2 billion. The country produces approximately 1.3 million tonnes of apples and pears per annum, with a value of ZAR8 billion.[50]

*M. fructicola* is not known to occur in South Africa and is regarded as a quarantine pest listed on various phytosanitary import requirements of many export countries. However, *M. fructicola* is endemic to North American countries, although it is also found in Asia and Oceania.[63] The introduction of *M. fructicola* into European countries has raised concerns about the possible impact on stone fruit production in the region.[64] The European and Mediterranean Plant Protection Organization regarded *M. fructicola* as a quarantine pest up until 2001 across Europe.[15] Recently, stone fruit growing countries across Europe reported the presence of *M. fructicola;* as a result, it has been declared a regulated harmful pest in the European Union.[65,66] In terms of geographic distribution, *M. fructicola* is known to occur in Europe, Africa, North America, South America and Oceania.[67] Risk analysis per the US Animal and Plant Health Inspection Service – Plant Protection and Quarantine guidelines was conducted for *M. fructicola* (Table 2). Because of its vast host range, significant economic effect, widespread dissemination, and extensive geographic distribution, *M. fructicola* has a high pest potential.

**Table 2:** Risk ratings and scores from intercepted *Monilinia fructicola* generated from the imported *Prunus* spp. fresh fruit from Spain. The numeric value for the ranking that is used to generate the cumulative risk rating is the number in brackets following the risk rating. Each risk factor is assigned a score of high, medium, or low.

| Risk element | ***Monilinia fructicola*** |
|---|---|
| Consequences of introduction | |
| Climate/host interaction | High (3) |
| Host range | High (3) |
| Dispersal potential | High (3) |
| Economic impact | High (3) |
| Environmental impact | Medium (2) |
| Likelihood of introduction | |
| Quantity imported | High (3) |
| Survive post-harvest treatment | High (3) |
| Survive shipment | High (3) |
| Not detected on entry | Medium (2) |
| Moved to suitable habitat | Medium(2) |
| Find suitable host | High (3) |
| Pest risk potential (risk score) | 30 |

To manage diseases in exporting countries, growers are encouraged to remove and destroy mummified fruits and infected tissues to reduce the inoculum potential during winter months. The residues of pruning must be destroyed or inactivated. After blossoming, infected or symptomatic twigs and branches must be removed. Any infected fruit must be destroyed. Growers are encouraged to improve ventilation and insulation by green pruning and herbicides to avoid excess moisture.

Pre-harvest treatments include a minimum of three sprays of fungicide during bloom and a further three sprays 28 days before harvest, with the last application not more than 10 days before harvest. Resistance against the benomyl, dicarboximides and demethylation-inhibiting fungicides (Cyproconazole, Difenoconazole, Fenbuconazole, Tebuconazole) have been reported in countries where fungicides have been used regularly.[68] All isolates of *M. fructicola* tested from Spain showed resistance to benzimidazole fungicides and a few of these isolates showed resistance to dicarboximide fungicides.[69] An anti-resistance strategy must be implemented to prevent the development of pesticide resistance.[70,71]

Exporting countries are encouraged to inspect each registered production site for *M. fructicola* at least 6 weeks before harvest. A sample of 600 fruits must be withdrawn from each production site registered for export to South Africa during inspection. This sampling procedure provides a 95% confidence level for detecting infested fruit if the infestation rate is 0.5% or higher. The sample must be sent to a laboratory for *Monilinia* spp. diagnosis and treated with paraquat[72] or freeze-treated[28] and cultured in a humid chamber in the laboratory. Fruit showing brown rot must be tested by polymerase chain reaction (PCR) in accordance with one of the identification techniques for *M. fructicola.*[37,68,69] If the result of the PCR testing for *M. fructicola* is positive, the production site must be rejected for export to South Africa.

During post-harvest inspection and testing, a sub-sample of 750 or 630 fruits must be taken from a sample (i.e. 143 packing units from a consignment of 2000 packing units or less or 150 packing units from a consignment with more than 2000 packing units) for *M. fructicola*. The sub-sample must be sent to a laboratory for *M. fructicola* diagnosis. Fruit that has been thinned and left on the orchard floor can be a substantial inoculum source for secondary infections.[12] Brown rot should be reduced in nectarine and potentially other stone fruit orchards by removing or destroying thinned fruit. Quiescent fungal infections can affect green, immature, and mature sweet cherry fruit, and they can be apparent or invisible.[71,73] Even if the inoculum is consistently high and the environmental conditions are favourable in an orchard, the risk of fruit brown rot at different developmental stages may vary due to seasonal changes in fruit susceptibility.[59,74] *M. fructicola* is an economically important pathogen, causing brown rot symptoms on several plant hosts.[75]

## Conclusion

The reported interceptions of *M. fructicola* were all found on stone fruits imported to South Africa from Spain. This species of fungus is a quarantine pest for South Africa and is currently listed in various phytosanitary import requirements for the importation of fresh fruits and propagation materials to South Africa.

The phytosanitary concern is that *M. fructicola* could survive, develop, reproduce, and spread under favourable conditions. Furthermore, various host plants in South Africa are associated with the disease. We recommend that fresh fruits of *Prunus* spp. samples should undergo a systems approach in the exporting country to minimise the risk of transport of *M. fructicola*. In addition, a visual inspection should be conducted, but it should not be the only phytosanitary intervention. Recommended phytosanitary measures should include pre-harvest control in the orchards, pest free areas/places of production, a pre-harvest inspection of fruits and testing, post-harvest inspection and testing, and cultural practices including removal and destruction of mummified fruits and infected tissues.

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## Competing interests

We have no competing interests to declare.

## Authors' contributions

P.P.T.: Conceptualisation; writing – initial draft; writing – revisions. L.R.N. and T.C.M.: Conceptualisation; writing – revisions; final approval of the manuscript.

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# Statistical modelling to predict silicosis risk in deceased Southern African gold miners without medical evaluation



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The Qhubeka Trust was established in 2016 in a legal settlement on behalf of former gold miners seeking compensation for silicosis contracted on the South African mines. Settlements resulting from lawsuits on behalf of gold miners aim to provide fair compensation. However, occupational exposure and medical records kept by South African mining companies for their employees have been very limited. Some claimants to the Qhubeka Trust died before medical evaluation was possible, thus potentially disadvantaging their dependants from receiving any compensation. With medical evaluation no longer possible, a statistical approach to this problem was developed. The records for claimants with medical evaluation were used to develop a logistic regression prediction model for the likelihood of silicosis, based on the potential predictors: cumulative exposure to respirable dust, age, years since first exposure, years of life lost prematurely, vital status at 31 December 2019, and a history of tuberculosis diagnosis. The prediction model allowed estimation of the likelihood of silicosis for each miner who had died without medical evaluation and is a novel approach in this setting. In addition, we were able to quantitatively evaluate the trade-offs of different silicosis risk classification thresholds in terms of true and false positives and negatives.

**Significance:**

- A statistical approach can be used for risk estimation in settings where the outcome of interest is unknown for some members of a class.
- The likelihood of silicosis in deceased miners without medical evaluation in the Qhubeka Trust can be accurately estimated, using information from finalised claims.
- Strategies for classifying the silicosis status of deceased miners without medical evaluation in the Qhubeka Trust can be assessed in a rigorous, quantitative framework.

## Introduction

A settlement arising out of a lawsuit against Anglo American South Africa Limited and AngloGold Ashanti led to the establishment of the Qhubeka Trust to process the claims for silicosis of a closed list of 4365 named gold miner claimants. The claims process required each claimant, or, where the claimant was deceased, their dependant, to formally lodge a claim, and for the claimant to be medically examined to determine whether they had a compensable silica-related disease as set out in the Trust Deed. In the case of deceased claimants, the dependants were required to provide medical information on which to base a diagnosis.

Provision16.2 (ii) (1) of the Trust Deed specifies that dependants may qualify for compensation (but only at the lowest level) based on medical records, employment records, or other evidence that the Trustees deem 'credible and reliable'. There are 466 deceased Qhubeka Trust claimants for whom a claim was lodged by their dependants, but for whom there is no, or insufficient, medical information on which to base a diagnosis of silicosis. In addition to requesting medical records from the deceased's dependants, various avenues of enquiry undertaken by the Qhubeka Trust to obtain medical information for these claimants have had limited or no success. It is notable that the silica exposure and occupational medical information kept by mining companies for their employees has historically been incomplete, and, in many cases, non-existent. Without such medical documentation, or any other means to determine the possible presence of silicosis, family members of deceased claimants, or, as described in the Trust Deed, 'dependent claimants', may be disadvantaged from receiving compensation to which they may be entitled.

The benefit award to Qhubeka Trust qualifying claimants is paid in two tranches – the first when the claim has been processed and the claimant is determined to have met all qualifying criteria, and the second and larger when the totality of claims for all claimants have been medically assessed and finalised. Consequently, by the end of 2019, by which time all the living claimants had been medically evaluated, finalisation of payment of equitable benefits to all claimants was being held up by the indeterminate silicosis status of the 466. There was therefore some urgency to identify an approach that would enable equitable evaluation of claims from this group of deceased ex-miners, as the second and final payment to qualifying claimants could not be made until all outstanding claims (the 466 deceased claims) were finalised. At that point, all available benefit funds could be distributed equitably.

In light of challenges with obtaining medical information for deceased claimants, the Trustees approached us to determine whether it was possible, by means of statistical modelling, to estimate the probability of deceased claimants with insufficient medical information having had silicosis at the time of their deaths.

A statistical prediction model, novel in this context, but using well-established statistical methodology, was developed to predict likelihood of silicosis for each deceased miner without medical evaluation.

## Materials and methods

A Microsoft Excel database with anonymised available information on all claimants was supplied by the Qhubeka Trust for the purpose of this study only. The data otherwise remain under the confidential control of the Trust. Clause 12.4 of the Qhubeka Trust Deed provides that:

> *The trustees have great power to use, publish or disseminate in anonymised form and without profit or payment, the information and data gathered during the course of the operation of the Trust solely for the purpose of advancing public health.*

A prediction model for the risk of silicosis was developed, based on the silicosis status of the 'Modelling group', consisting of those claimants who had been medically assessed for the presence of silicosis, and for whom there was complete information on the potential predictors. The 'Prediction group' consisted of the deceased miners without medical evaluation.

The statistical methodology used is well established, but the application in this setting is novel.

Based on associations reported in the literature[1-15] and data availability, the potential predictors of silicosis risk that we considered are listed in Table 1. All variables were examined for potential errors and missing values which might limit numbers of individuals who could be included in the analyses.

**Table 1:** Potential predictors of silicosis diagnosis

| Predictor variable | Description |
|---|---|
| Cumulative exposure | This was calculated [by JEM] from each claimant's total years of recorded service multiplied by the average respirable dust concentration in mg-years/m³ (as reported in the literature[2-7,9,11,12]) for their main job |
| Age | Age in years at 31 December 2019 (for deceased claimants this was the age they would have attained at this date) |
| Latency | Years from start date working on mines to claim date at the Qhubeka Trust |
| Years of life lost | Years of life lost prematurely by those who died before 31 December 2019. For claimants alive at that date this is zero. |
| Vital status | Vital status at 31 December 2019 (0 = alive, 1 = deceased) |
| History of tuberculosis | Tuberculosis diagnosis (0 = no, 1 = yes) |

Initial exploratory data analysis was conducted in the Modelling group, including cross-tabulations of silicosis status with categorical predictor variables (vital status at 31 December 2019 and historical diagnosis of tuberculosis), and non-parametric smoothed plots versus risk of silicosis for continuous predictor variables (cumulative exposure to respirable dust, age at 31 December 2019, latency, and years of life lost).

Because all claimants in the Prediction group are deceased, one option considered was to base prediction modelling just on the deceased in the Modelling group, this being the subgroup that best parallels the Prediction group. We elected rather to develop prediction models based on all claimants in the Modelling group, while including vital status as a predictor, because information from alive claimants would inform other aspects of silicosis risk such as cumulative exposure.

We considered the following predictors in three logistic regression models with silicosis (yes/no) as the outcome:

M1: cumulative dust exposure, age, years of life lost, latency, vital status, tuberculosis

M2 (allowing for non-linearity of the continuous predictors, cumulative exposure and age): linear + quadratic cumulative dust exposure, linear + quadratic age, years of life lost, latency, vital status, tuberculosis

M3 (without latency): linear + quadratic cumulative dust exposure, linear + quadratic age, years of life lost, vital status, tuberculosis

The fitted models yielded predicted risks of silicosis for all claimants in both the Modelling and Prediction groups. Towards exploring risk thresholds to classify claimants in the Prediction group as silicosis positive/negative, Tables 2 and 3 introduce and define the terminology associated with classification accuracy. True positives (TPs) and negatives (TNs), false positives (FPs) and negatives (FNs) are the building blocks for calculating sensitivity, specificity, positive and negative predictive values (PPV and NPV) and the proportion correctly classified. PPV, NPV and proportion correctly classified depend on the prevalence ($n_1$/N) of the disease under consideration, while sensitivity and specificity do not.

**Table 2:** Terminology used in assessing classification accuracy

| | | True disease status | | |
|---|---|---|---|---|
| | | **Positive** | **Negative** | |
| **Model disease classification** | **Positive** | True positive (TP) | False positive (FP) | A |
| | **Negative** | False negative (FN) | True negative (TN) | B |
| | | $n_1$ | $n_2$ | N |

**Table 3:** Definitions of classification accuracy characteristics

| Term | Definition |
|---|---|
| Risk classification threshold | A classification rule such that all individuals with a predicted risk at or above the threshold would be classified as positive for disease |
| Sensitivity | The proportion of individuals who are classified positive among all those who actually have the disease (TP/$n_1$) |
| Specificity | The proportion of individuals who are classified negative among all those who actually do not have the disease (TN/$n_2$) |
| Positive predictive value (PPV) | The proportion of individuals who actually have the disease among all those who are classified positive (TP/A) |
| Negative predictive value (NPV) | The proportion of individuals who actually do not have the disease among all those who are classified negative (TN/B) |
| Proportion correctly classified | The proportion of individuals who are correctly classified (TP+TN)/N |

The receiver operating characteristic (ROC) curve plots sensitivity versus 1-specificity at each possible risk classification threshold. For each of the models we considered, we estimated the associated area under the ROC curve (AUC). AUCs can take on values from 0.5 to 1.0 and provide a measure of the model's ability to discriminate between those subjects who experience the outcome of interest (here, silicosis) versus those who do not. A model with AUC of 0.5 is no better than a coin toss; AUCs in the range 0.7–0.8 are regarded as reflecting a prediction model with acceptable discrimination, 0.8–0.9 as excellent discrimination and above 0.9 as outstanding discrimination.[16] We used likelihood ratio tests to compare models and the final model was chosen as the model with the minimum Akaike Information Criterion (AIC)[17] among competing models.

For the final model, we assessed the goodness of fit of the silicosis risk predictions applied to the Modelling group graphically and quantitatively by the Hosmer–Lemeshow and Stukel goodness-of-fit tests.[16,18,19] We estimated the accuracy characteristics of the final model (sensitivity, specificity, PPV, NPV and per cent correctly classified) for silicosis classifications, according to different thresholds of predicted risk, focusing on the subgroup of deceased claimants in the Modelling group, which was considered to be most comparable to the deceased claimants in the Prediction group, including with regard to likely prevalence of silicosis.

Accuracy characteristics estimated from the same data on which a model was developed may be 'optimistic', i.e. may be more favourable than if the model was applied to new data. We assessed optimism in measures of AUC and accuracy by bootstrapping.[20]

STATA version 13.1 was used for analysis.

## Results

Figure 1 shows the finalisation status of Qhubeka Trust claims at the end of December 2019. At that date, 3369 claimants (2993 living and 376 deceased) had been medically assessed and their claims finalised. Of the claimants with finalised claims, 58% were diagnosed with silicosis and 63% had a history of tuberculosis diagnosis.

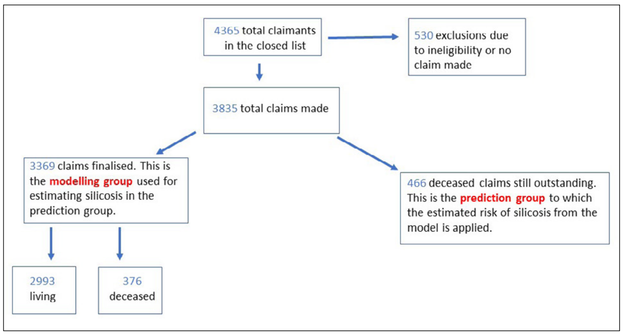


**Figure 1:** Finalisation status of Qhubeka Trust claimants as of 31 December 2019.

Of the 3369 claimants with diagnosis in the Modelling data, there were 220 for whom cumulative exposure could not be determined (because length of service was not known) and 16 for whom age (at 31 December 2019) could not be determined (because date of birth was not known). Additionally, latency could not be determined for a further 22 of these claimants, because either start date of employment at the mines or claim date was not known. Analyses were restricted to claimants with complete records, i.e. $n=3111$ for analyses including latency, and $n=3133$ for analyses without this variable.

Table 4 shows summaries of silicosis predictor variables in the Modelling group by silicosis diagnosis status, for the 3133 claimants with complete data on all predictor variables except latency (22 missing) and in the Prediction group ($n=466$, 10 missing latency). Claimants with silicosis had higher cumulative exposure to respirable dust, more years of life lost among the deceased, were more likely to be deceased by 31 December 2019, and were more likely to have been diagnosed with tuberculosis.

**Table 4:** Characteristics of claimants in the Modelling (by silicosis diagnosis) and Prediction groups

| | Silicosis ($n=1897$) | No silicosis ($n=1236$) | Prediction group ($n=466$) |
|---|---|---|---|
| **Predictor variables** | **Median (range)** | | |
| Cumulative exposure (mg/m³ years) | 5.8 (0.11, 24.4) | 3.3 (0.05, 20.8) | 4.9 (0.2, 15.8) |
| Age on 31 December 2019 | 66.6 (47.8, 105.6) | 63.0 (34.6, 93.0) | 68.5 (48.2, 97.1) |
| Years of life lost if deceased (relative to 31 December 2019)[a] | 3.7 (0.1, 20.0) | 2.2 (1.5, 2.9) | 4.9 (1.0, 15.3) |
| Latency (years)[b] | 38.0 (10, 63) | 37.0 (9, 62) | 38.9 (21, 69) |
| | ***n* (column %)** | | |
| Deceased by 31 December 2019 | 348 (18.3 %) | 13 (1.05%) | 466 (100%) |
| Tuberculosis | 1414 (74.5%) | 586 (47.4%) | 199 (42.7%) |

[a]*Modelling group:* n=*348 and* n=*13 with and without silicosis, respectively.*

[b]*Modelling group:* n=*1886 and* n=*1225 with and without silicosis, respectively (22 missing); Prediction group:* n=*456 (10 missing).*

Of the 3133 claimants with complete data in the Modelling group who were alive at 31 December 2019, 55.9% had been diagnosed with silicosis, while, of the claimants deceased at that date, 96.4% had been diagnosed with silicosis. It is evident that deceased status is strongly related to presence of silicosis. Of the 361 deceased miners in the Modelling group with complete records, only 13 had not been diagnosed with silicosis.

### *Model development*

Table 5 shows the AUC and AIC for each model (M1, M2, M3) as well as the *p*-values for the likelihood ratio test comparing M2 to M1 and M3 to M2.

**Table 5:** Comparison of models for predicting risk of silicosis

| Model | Area under the curve | Akaike Information Criterion | Likelihood ratio test *p*-value |
|---|---|---|---|
| M1 | 0.772 | 3437.7 | – |
| M2 | 0.774 | 3425.5 | 0.0003[a] (M2 cf M1) |
| M3 | 0.774 | 3423.6 | 0.725[b] (M3 cf M2) |

[a]*Tests the null hypothesis that the quadratic terms for cumulative exposure and age are zero.*

[b]*Tests the null hypothesis that the coefficient for latency is zero.*

Characteristics of all three models considered were similar, but our examination of competing models indicated that latency did not contribute significantly to model fit and that the model was improved with inclusion of quadratic terms for cumulative exposure and age. On this basis, model M3 was chosen as the final model for prediction and refitted, using the 3133 records with complete data (excluding latency). The refitted model was associated with estimated AUC=0.78 or, when restricted to deceased claimants, AUC=0.82. The coefficients for this final model are shown in Table 6 and the associated ROC curves are shown in Supplementary figure 1.

**Table 6:** Final model to predict risk of silicosis[a]

| Predictor variable | Estimated coefficient | Odds ratio | *p*-value |
|---|---|---|---|
| Linear cumulative exposure (mg-years /m³) | 0.1810 | 1.20 | <0.001 |
| Quadratic cumulative exposure | -0.0079 | 0.99 | 0.002 |
| Linear age (years) | 0.0438 | 1.04 | <0.001 |
| Quadratic age | -0.0014 | 0.99 | 0.003 |
| Years of life lost | 0.4646 | 1.59 | 0.014 |
| Vital status | 1.4983 | 4.47 | 0.004 |
| Tuberculosis | 1.1152 | 3.05 | <0.001 |
| Intercept | -0.3113 | – | <0.001 |

[a]*The coefficients in the table can be used to calculate probability estimates for any given predictor values, using the logistic equation. Cumulative exposure is centred at 5 mg-years/m³ and age is centred at 65 years. The odds ratios are provided additionally for ease of interpretation.*

The odds of silicosis are estimated to be 4.5 times higher in individuals who are deceased than those still alive at 31 December 2019 (among individuals with the same exposure, age, tuberculosis status and years of life lost). For every additional year of life lost, odds of silicosis are estimated to increase by a multiple of 1.59. The odds of silicosis are estimated to be 3.05 times higher in individuals with tuberculosis than those without (among individuals with the same exposure, age, vital status and years of life lost). (The odds ratios for cumulative exposure and age cannot be directly interpreted, because of the quadratic terms.)

Table 7 summarises the predicted risks of silicosis in the Modelling group, stratified by vital status, and in the Prediction group. It is notable that the predicted risks of silicosis in both deceased groups are high (all above 70%) and that they have very similar ranges.

**Table 7:** Predicted risk of silicosis

| Claimant group | Predicted risk of silicosis [Mean (minimum, maximum)] |
|---|---|
| Modelling: Alive | 0.5588 (0.0620, 0.8973) |
| Modelling: Deceased | 0.9640 (0.7024, 1.0000) |
| Prediction | 0.9616 (0.7055, 0.9996) |

## *Model evaluation*

A goodness-of-fit comparison of observed and expected (from the M3 prediction model) numbers of silicosis cases in predicted risk deciles is shown in Table 8 and graphically in Supplementary figure 2. Both indicate that the model fits the data well. The *p*-values for the Hosmer–Lemeshow and Stukel goodness-of-fit tests for this model (M3) were $p=0.46$ and $p=0.87$, respectively; both also indicate good fit.

**Table 8:** Comparison of observed and expected (under M3) counts with and without silicosis by predicted risk deciles

| Decile | Predicted risk | Observed with silicosis | Expected with silicosis | Observed without silicosis | Expected without silicosis | Total |
|---|---|---|---|---|---|---|
| 1 | [0, 0.273] | 69 | 67.2 | 245 | 246.8 | 314 |
| 2 | (0.273, 0.381] | 93 | 101.7 | 220 | 211.3 | 313 |
| 3 | (0.381, 0.475] | 143 | 134.7 | 170 | 178.3 | 313 |
| 4 | (0.475, 0.552] | 162 | 160.6 | 152 | 153.4 | 314 |
| 5 | (0.552, 0.621] | 193 | 183.5 | 120 | 129.5 | 313 |
| 6 | (0.621, 0.684] | 189 | 204.5 | 124 | 108.5 | 313 |
| 7 | (0.684, 0.749] | 223 | 225.5 | 91 | 88.5 | 314 |
| 8 | (0.749, 0.818] | 251 | 245.8 | 62 | 67.2 | 313 |
| 9 | (0.818, 0.924] | 269 | 267.1 | 44 | 45.9 | 313 |
| 10 | (0.924, 1] | 305 | 306.5 | 8 | 6.5 | 313 |

Supplementary figure 3 shows side-by-side box plots, by true silicosis status, of predicted risk of silicosis for all claimants in the Modelling group and for deceased claimants in the Modelling group. The greater the separation between the distributions of predicted risk in those with and without 'disease' (here, silicosis), the better the predictive performance of a model. Note that all deceased claimants in the Modelling group have predicted risk of silicosis above 70%.

## *Silicosis risk classification thresholds*

For the purposes of Qhubeka Trust claims, having estimated the likelihood of silicosis for each miner in the Prediction group, the question remains as to what level of predicted risk should be regarded as sufficient to classify a claimant as 'silicosis positive'. By 'risk classification threshold', we mean a classification rule such that all claimants with a predicted risk at or above the threshold would be classified as positive for 'disease' (here, silicosis). Typically, in deciding on a risk threshold, considerations are weighed as to the consequences of false positives (FPs) and false negatives (FNs), and the benefits of true positives (TPs) and true negatives (TNs). In some circumstances, it is a high priority to reduce FNs (missed cases), e.g. for a disease that has poor prognosis if untreated, or, as in the case of the Qhubeka Trust, to avoid qualifying claimants being denied compensation. In some circumstances, it may be a high priority to reduce FPs, e.g. when the next steps for those classified as positive are medically invasive. If avoiding FNs and FPs are of equal priority, one might consider selecting a risk threshold that maximises both sensitivity and specificity. However, this approach ignores the impact of the prevalence of the outcome of interest. If, for instance, a disease is common (i.e. has a high prevalence, as with silicosis in the deceased claimants), FNs will dominate the misclassified individuals compared with FPs. Sometimes it is possible to assign values to costs and benefits of false and true positives and negatives, and then choose a threshold which maximises the net benefit of a classification rule. In the absence of quantifiable costs and benefits, one approach, which does acknowledge prevalence to some extent, is to consider a risk threshold with the greatest percentage of correct classifications.

Our evaluation of silicosis risk prediction thresholds is based on the $n=361$ Modelling group claimants who are deceased, as this group most closely parallels the Prediction group, where all claimants were deceased. Note again, referring to Table 7, that the distributions of predicted risk in these two groups are very similar. Only 13 (out of 361) or 3.6% of the deceased in the Modelling group are true silicosis negative cases. This points again to the strong relationship between premature death and silicosis.

For the deceased claimants in the Modelling group, Supplementary figure 4 shows the estimated sensitivity and specificity at each potential risk classification threshold and Table 9 shows estimates of prediction accuracy for the following risk classification thresholds: 0.51–0.7, 0.75, 0.8, 0.85, 0.9, 0.95.

**Table 9:** Estimated model accuracy by risk threshold (Modelling group, 361 deceased claimants)

| Risk threshold | Percentage correct | Sensitivity | Specificity | Positive predictive value | Negative predictive value | False negative (FN; of 348 with silicosis) False positive (FP; of 13 without silicosis) |
|---|---|---|---|---|---|---|
| 0.51–0.7 | 96.4% | 100% | 0.00% | 96.4% | – | FN=0, FP=13 |
| 0.75 | 95.3% | 98.8% | 0.00% | 96.4% | 0.00% | FN=4, FP=13 |
| 0.80 | 94.7% | 98.3% | 0.00% | 96.3% | 0.00% | FN=6, FP=13 |
| 0.85 | 92.8% | 96.0% | 7.7% | 96.5% | 6.7% | FN=14, FP=12 |
| 0.90 | 89.5% | 92.2% | 15.4% | 96.7% | 6.9% | FN=27, FP=11 |
| 0.95 | 79.2% | 79.9% | 61.5% | 98.2% | 10.3% | FN=70, FP=5 |

In interpreting Table 9 and using it, and Supplementary figure 4, to guide consideration of an appropriate risk threshold to apply to the deceased claimants in the Prediction group, it must be kept in mind that:

- As the risk threshold to classify claimants as having silicosis increases, sensitivity will decrease and specificity will increase.
- Of the 361 deceased claimants with complete records in the Modelling group, only 13 were not diagnosed with silicosis, i.e. this group has 96.4% true silicosis positive cases (TP), and 3.6% true silicosis negative cases (TN).
- The lowest model-predicted risk of silicosis in these deceased claimants is 70.3%.
- Hence, risk thresholds at 70% or below would classify all Modelling group deceased claimants as positive for silicosis (0 FNs, 13 FPs).
- The lowest predicted risk of silicosis among the 13 deceased subjects without silicosis is 0.84 (see Supplementary figure 3).
- Hence, increasing risk thresholds up to 0.84 will simply increase FNs without reducing FPs, i.e. the impact of moving the risk threshold in Table 9 from 0.7 to 0.75 to 0.8 is simply to increase the number of FNs, while the number of FPs remains unchanged.
- For all thresholds considered here, the NPVs are low, i.e. if a claimant is classified as silicosis negative, there is a low probability of them actually being a true silicosis negative.
- By contrast, PPVs are high, i.e. if a claimant is classified as silicosis positive, there is a high probability of them actually being a true silicosis case.
- Because silicosis is so common in deceased claimants, a threshold with equal sensitivity and specificity (seen from Supplementary figure 4 to be above 0.95), would result in FNs far outweighing FP classifications.
- Of thresholds in the range 0.7–0.95, the highest percentage of correctly classified deceased claimants is 96.4% at a classification threshold of 0.7 or 70%.

### *Assessment of optimism*

Because estimates of model performance that use the same data to develop and evaluate models may be biased upward, i.e. optimistic, we carried out a bootstrap analysis to estimate the extent of optimism in the estimates of the above model characteristics (AUC, % correct, sensitivity, specificity). The estimated optimism for all characteristics was very small and hence no adjustment to the above estimates was required.

## Discussion

We have developed a model to predict silicosis risk based on a claimant's cumulative exposure to respirable dust, age, years of life lost prematurely, vital status and diagnosis of tuberculosis. We have demonstrated that the model fits the Modelling group data well and has excellent discriminating ability between those with and without silicosis. Based on this model, we can estimate the risk of silicosis for each claimant in the Prediction group, i.e. the deceased claimants without medical evaluation.

Estimates for the deceased claimants in the Modelling group lead us to anticipate that the fraction of non-silicosis claimants in the Prediction group will be small (3.6% of the deceased in the Modelling group). This also means that estimation of accuracy characteristics relating to true negatives, in particular, specificity, is constrained by the small number of deceased claimants without silicosis. However, examination of Table 9 makes it clear that any threshold which is chosen to improve specificity (which would reduce false positive classifications), will be at the cost of a disproportionate increase in false negative classifications (which would reduce sensitivity).

Silicosis risk classification thresholds were evaluated starting with 0.51 (51% and representing the balance of probabilities of having silicosis) and ranging to 0.95 (95%). A threshold of 0.7 (70%) was associated with the highest per cent of correct classifications (96.4%) and the highest estimated sensitivity (100%: no true cases of silicosis missed), while the very small number of false positives (those without silicosis misclassified as having silicosis) remained more or less constant up to a threshold of 0.9 (90%).

Consideration of risk classification thresholds includes weighing the consequences for the Qhubeka Trust claimants of false negative and false positive classifications. The dependants of FN claimants would be denied compensation to which they are entitled. On the other hand, the consequences of FPs among the deceased Qhubeka Trust claimants are benefits in the form of compensation, i.e. there is no disadvantage to these individuals. Furthermore, we project that the number of true negatives is very small and hence the compensation benefit disadvantage to the entire group of claimants of a risk classification threshold that classifies all undiagnosed claimants as silicosis positive, is also very small, particularly as this is spread over a large number of beneficiaries, and consequently minimally impactful.

A silicosis risk threshold of 70% accords with the highest percentage of claimants being correctly classified, and constitutes the classification rule with the highest sensitivity, with little improvement in specificity at higher risk thresholds up to 90%. All 466 members of the Prediction group have a predicted silicosis risk greater than 70%. If a risk classification threshold of 0.7 (70%) is chosen, then all claimants in this group will be classified as having silicosis at the time of their death.

We note the poor state of employee record-keeping by the mining employers, even for such basic information as individual miners' ages, as well as jobs worked, length of service in these jobs over their careers, their exposures in these jobs, and their health records over many years. This has consequences for claimants with silica-related diseases who may be unable to show their eligibility for benefit. This situation is despite the mining industry having been enjoined as far back as the 1960s21(p.232) to institute a system of integrated individual mining medical records for black miners that encompasses their individual measures of cumulative exposure. The models developed and applied here might have had even greater accuracy with better record-keeping and monitoring by employers. Indeed, the models would have been unnecessary if the silicosis status of the deceased in the Prediction group had been known.

## Conclusions

The situation faced by the Qhubeka Trust, where medical records of deceased claimants are not sufficient to provide clear assessment of silicosis, is one that will be encountered in other settings. For instance, a 2018 study22 estimated that, at that time, more than 100 000 miner compensation claims in southern Africa were still unpaid. It is very likely that the administration of such claims will face the same challenges of miners who will have died before medical evaluation. The approach we have described here gives hope that it is still possible, in a scientifically robust manner, to address the eligibility of such claimants.

## Competing interests

Both authors were paid as consultants by the Qhubeka Trust to undertake the research presented in this article.

## Authors' contributions

Both authors were involved in every aspect of the study: conceptualisation; methodology; data acquisition and cleaning; data analysis; validation; writing.

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# Increased risk of heat stress conditions during the 2022 Comrades Marathon

The Comrades Marathon is South Africa's – and the world's – most recognised and largest ultra-marathon event, with over 15 000 participants from across the globe competing in the 89-km road running event each year. Historically, the event has been held before the start of austral winter (20 May – 17 June). However, in 2022, organisers of the race moved the event to 28 August, when austral spring commences. We explore the climate, in particular the Universal Thermal Comfort Index (UTCI), of past Comrades events (1980-2019) and compare these data to UTCI data of the new proposed date (28 August) for the same period. The climatology for May, June, July and August was determined to identify periods with the lowest risk for 'strong' to 'very strong' heat stress. Results show that participants' risk of exposure to 'strong' heat stress and 'very strong' heat stress periods will be more likely if the event is held in August as compared to the original event dates. Therefore, it is concluded that mid-June to mid-July has the lowest risk of heat stress exposure along the route. Runners and organisers should be aware of the higher risk of exertional heat illness during the 2022 Comrades Marathon to ensure safe participation.

**Significance:**

- The new proposed date for the Comrades Marathon will increase the risk of exposure to 'strong' and 'very strong' heat stress conditions, as defined by the Universal Thermal Comfort Index (UTCI).
- The UTCI indicates that mid-June to mid-July has the lowest risk of heat stress exposure at the three reference points along the route.
- Organisers should warn runners of the higher risk of exertional heat illness due to the possible exposure to high UTCI values or more unfavourable climatological conditions. Furthermore, runners should be informed of a variety of preventative strategies to ensure safe participation.

## Introduction

The Comrades Marathon is a 89-km road-running event between Durban and Pietermaritzburg in the Kwazulu-Natal Province of South Africa, and is perhaps the most recognised ultra-running event in the world.[1] The event was first hosted in 1921, and despite disruptions during World War 2 (1941–1945) and more recently during the COVID-19 pandemic (2020–2021), has been hosted on 94 occasions, making it the world's oldest ultra-marathon.[1,2] Since 1980, the race dates were set either for the last week of May or for the first two weeks of June, with the earliest race date set as 20 May in 1995 and the latest date as 17 June in 1996, 2002 and 2007. Therefore, the race dates usually fall within early austral winter. However, in 2021, the event organisers announced that the Comrades Marathon of 2022 will be held on 28 August, two days before the start of austral spring. Organisers cited the extended daylight as a motivating factor for hosting the event in August, stating that the temperatures are still safe enough to host the event during this time.[3] Despite this notion, there is no indication that event organisers examined climatological data to verify their decision. Heat stress in athletes can have potentially catastrophic health and performance consequences, which justify the importance of doing an in-depth study of possible changes in climatological conditions that runners will face due to the new start date.

Exertional heat illness, which encompasses exercise associated with collapse due to heatstroke, is the most common medical attention-requiring condition that athletes experience during participation in marathons.[4] High temperature and humidity seem to be significant factors for developing exertional heat illness in athletes.[5,6] However, athletes are also at risk of attaining lower performance levels. Exercise capacity (time to exhaustion) decreases together with an increase in perceived exertion as environmental temperature and relative humidity increase.[7] Contrary to previous research, more recent research concluded that the performances of top-level marathon runners show higher decreases in performances due to higher temperatures than do slower runners.[6] This trend in results was attributed to the assumption that top-level runners work at a higher intensity than their slower counterparts and will probably surpass their physiological limits to cope with the adverse effects of heat stress.[6] The possible mechanisms that underlie the risk of developing heat illness and attaining lower performance levels when exercising in hot and humid conditions are: the extra cardiovascular strain that is caused by a redistribution of blood to cutaneous vascular beds together with the maintenance of perfusion due to exercising muscle oxygen delivery; an exacerbated reduction in cerebral blood flow via central inhibition; the downregulation of skeletal muscle recruitment via lower central neural drive; and a progressive shift in energy substrate mobilisation to the utilisation of more glycogen and less fat.[8]

The risk for exertional heat illness is high when the wet bulb globe temperature exceeds 28 °C during especially higher-intensity exercises (≥75% of $\dot{V}O_2max$) and/or when strenuous exercise is performed for longer than 1 hour.[7] Although various studies made use of the wet bulb globe temperature as a measure for assessing heat stress in athletes[9], the Universal Thermal Comfort Index (UTCI) is regarded to be a better measure to model sports heat stress[10]. Therefore, the UTCI was previously used to examine the effect of different thermal conditions on runners during 12 New York City Marathons and the risk of heat stress during the 2021 Olympics marathon by evaluating the sensation index.[6,9,11] The expected daily incidence rate of heat-related illness among athletes who participated in international outdoor World and European athletics championships between 2009 and 2019 increased by 0.14 per 1000 registered athletes for each degree of increase in UTCI, doubling from 25 to 35 UTCI.[12]

The last-mentioned researchers reported no severe heat illness below a UTCI value of 28. They also found that athletes who participated in endurance disciplines experienced a higher incidence of heat illness than those who participated in explosive disciplines.[11]

These findings provide a guideline according to which climatological conditions can be interpreted to ascertain the possible risk athletes face of experiencing exertional heat illness or a decrease in running performance. Therefore, the purpose of this research was to examine the climate of the past 40 Comrades Marathon events (1980–2019). Particular focus was placed on the UTCI as an indicator of heat stress to examine the possible prevalence of heat stress among runners and predict the possible influence of a change in climatological conditions on the incidence of exertional heat illness among athletes if the event is held in August.

## Data and methods

The Comrades Marathon takes place in KwaZulu-Natal, South Africa, between Pietermaritzburg and Durban. The event alternates annually between the 'up run' (Durban to Pietermaritzburg) and 'down run' (Pietermaritzburg to Durban). The starting point of the event within the respective cities has varied over the past 100 years, creating some differences in the final distance. However, the distance has consistently remained between 87 km and 91 km (see Figure 1 for the region of interest and route map, as well as the mean temperature climatology for August in the region). We examined the climate of Comrades Marathon events between 1980 and 2019 (as seen in Table 1). All events before 1980 were omitted from the analysis to match the temporal range of the ERA5 (the fifth-generation reanalysis global atmosphere data set from the European Centre for Medium-Range Weather Forecasts (ECMWF)).[13] The last Comrades was completed in 2019 before COVID-19 restrictions led to the event's cancellation in 2020 and 2021.

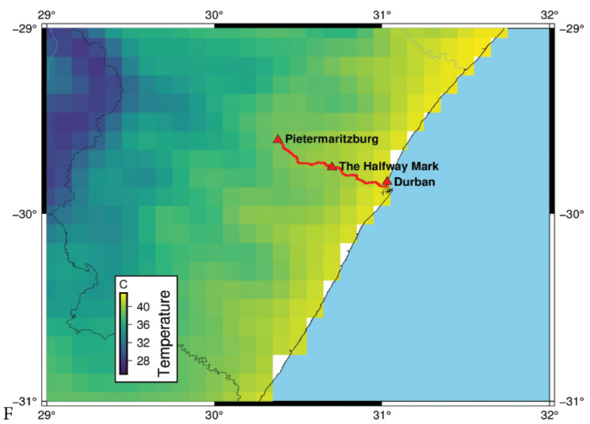


**Figure 1:** Mean temperature climatology (derived from ERA-5 2-m temperature) for August in the region of interest is represented here as an indication of the temperature gradient between the coastal and inland areas along the route. Indicated on the map are Pietermaritzburg, the halfway mark and Durban in KwaZulu-Natal, South Africa and the route on which the Comrades Marathon takes place.

ERA5 reanalysis data from the ECMWF was used to perform the climate analysis. A nearest-neighbour extraction was used to gather the historical climate at three points, namely: Pietermaritzburg (-29.6019, 30.3794), Durban (-29.8277, 31.0305) and the halfway mark (-29.7494, 30.7022). The new generation ERA5 reanalysis data has a resolution of 0.25° x 0.25° and a single grid cell is effectively ~30 km. Along the 90-km route, these points served as good reference points to ascertain the weather conditions experienced. The UTCI was derived from the ERA5 data set, calculated as a function of 2-m air temperature, 2-m dew point temperature (or relative humidity), wind speed at 10 m above ground level and mean radiant temperature. The UTCI was originally developed to indicate the possible physiological responses that humans will experience because of a combination of climatological factors[14-17]: air temperature (°C), wind speed (m/s), mean radiant temperature (°C) and humidity ratio (0–100). The UTCI values, together with the predicted associated physiological responses that athletes may experience, are detailed in Table 2.

**Table 1:** Comrades dates used in the analysis. May events are unshaded and June events are shaded in grey.

| 1980s | 1990s | 2000s | 2010s |
|---|---|---|---|
| 1980-05-31 | 1990-05-31 | 2000-06-16 | 2010-05-30 |
| 1981-05-31 | 1991-05-31 | 2001-06-16 | 2011-05-29 |
| 1982-05-31 | 1992-05-31 | 2002-06-17 | 2012-06-03 |
| 1983-05-31 | 1993-05-31 | 2003-06-16 | 2013-06-02 |
| 1984-06-01 | 1994-05-31 | 2004-06-16 | 2014-06-01 |
| 1985-05-31 | 1995-05-20 | 2005-06-16 | 2015-05-31 |
| 1986-05-31 | 1996-06-17 | 2006-06-16 | 2016-05-29 |
| 1987-05-31 | 1997-06-16 | 2007-06-17 | 2017-06-04 |
| 1988-05-31 | 1998-06-16 | 2008-06-13 | 2018-06-10 |
| 1989-05-31 | 1999-06-16 | 2009-05-24 | 2019-06-09 |

**Table 2:** ERA5-UTCI (Universal Thermal Comfort Index) values and predicted associated physiological stress response[14-17]

| UTCI | Physiological response |
|---|---|
| < -40 | Extreme cold stress |
| -27 to -40 | Very strong cold stress |
| -13 to -27 | Strong cold stress |
| 0 to -13 | Moderate cold stress |
| 0 to 9 | Slight cold stress |
| 9 to 26 | No thermal stress |
| 26 to 32 | Moderate heat stress |
| 32 to 38 | Strong heat stress |
| 38 to 46 | Very strong heat stress |
| > 46 | Extreme heat stress |

The UTCI values together with the predicted associated physiological responses were used to examine the possible risk for exertional heat illness, and particular focus was placed on 'strong' heat stress and 'very strong' heat stress periods along the three reference points. A time-series analysis revealed the risk for the occurrence of heat stress for different daily times and event dates. Subsequently, the analysis revealed the relative frequency (%) of 'strong' and 'very strong' heat stress values per month as indicated by the UTCI values >32.

## Results and discussion

The purpose of this study was to conduct an UTCI climatological analysis over the 1980–2021 period for the months of May, June, July and August, to examine the suitability of the new race date for the 2022 Comrades Marathon. Historically, the event was hosted in late May until 1996 when the event was moved to mid-June (Table 1). Due to the route's length, the UTCI was determined at three reference points (i.e. Durban, 'the halfway mark' and Pietermaritzburg) for separate analysis. Runners are prevented from competing further if they reach the halfway mark later than 11:45:00 (SAST). The grid cell at the halfway mark can also be used as a proximity location for the ~30-km radius along the route from this point, where the majority of runners who compete over 9 hours would be exposed to maximum midday heat stress conditions.

The climatology of the start and finish locations varied noticeably due to the coastal climatology of Durban and the inland climatology of Pietermaritzburg (Figure 1). We explicitly focused on 'strong' (32–38 UTCI) and 'very strong' (38–46 UTCI) heat stress periods during the study period. Extreme values only occurred 11% of the time over the duration of the whole climatology period. However, exposure to these periods can have an impact on athletes' performance. When examining the occurrence of 'strong' and 'very strong' heat stress days, Figure 2 indicates that the highest percentage of days with UTCI of 32–38, relative to May, June, July and August, is observed at the halfway mark during May (25.95%), followed by August (23.7%). The next highest percentage for high UTCI values was observed for Durban during May (21.5%) and August (15.63%). The percentage of UTCI that reached values higher than 38 UTCI during June and July was low for all reference points, with percentages that varied between 0% and 3.49%. In addition, Pietermaritzburg was the reference point for which the lowest percentages of 'strong' heat stress periods were identified during all months. Values for this reference point were 0.20%, 0%, 0% and 1.14% for May, June, July and August, respectively. The only reference points and periods for which 'very strong' heat stress periods (i.e. UTCI of 38–46) were observed, are Durban during May (0.23%) and August (0.39%) as well as at the halfway mark during August (0.20%).

The UTCI climatological data suggest that June and July are the months during which the periods of 'strong' and 'very strong' heat stress are fewer compared to both May and August. In addition, Pietermaritzburg served as the reference point with much lower percentages of 'strong' and 'very strong' heat stress periods compared to Durban and the halfway mark. From late July to August there is a noticeable increase in the frequency of heat stress days. The last 10 days of August also seem to produce higher occurrences of 'very strong' heat stress periods at Durban and the halfway mark (Figure 3) compared to the other days. Although May and August seemingly have similar 'strong' and 'very strong' heat stress days (Figure 2), historically, races have always been held during late May, when temperatures are cooling down (Figure 3). In contrast, the new proposed date is at the end of August when there is a significant increase in the occurrence of heat stress periods. A comparison by means of a *t*-test between the heat exposure risk of the last 10 days of May and the last 10 days of August indicated a statistically significant difference ($p<0.01$) between the two periods, with late August having a higher occurrence of 'strong' and 'very strong' heat stress periods compared to late May. A further comparison between the long-term climatology data of two 20-year periods, shows a 17% and 0.5% increase in 'strong' and 'very strong' heat stress days, respectively, from the 1980–2000 period to the 2001–2021 period. The largest increase in 'strong' heat stress days was observed at the halfway mark (11% increase), followed by Durban (5%) and Pietermaritzburg (1%).

Figure 4 indicates the historical year-on-year increase in 'strong' and 'very strong' heat stress conditions during the period of interest, likely as

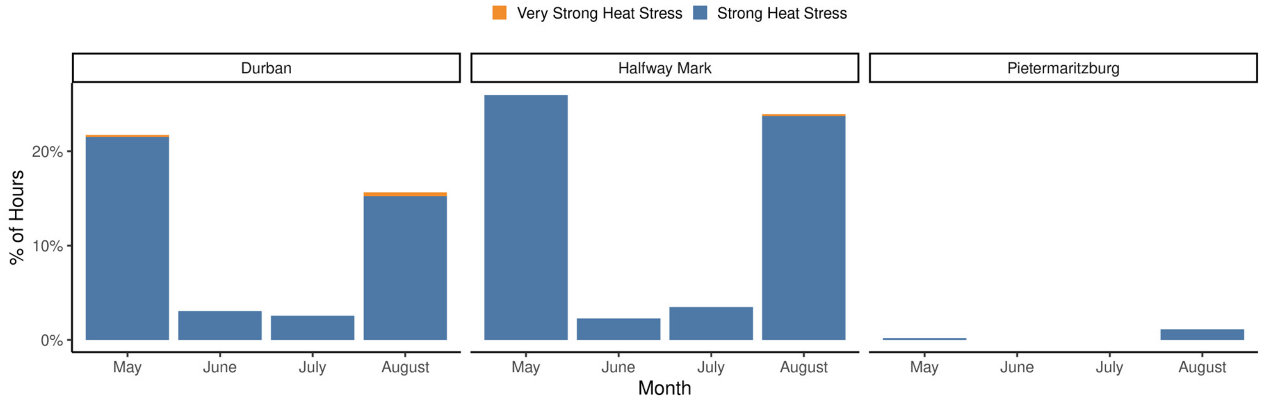


**Figure 2:** Distribution of 'strong' and 'very strong' heat stress hours between May and August (1980–2021) and location along the route. As a total of all WHO heat stress categories, 'strong' heat stress and 'very strong' heat stress days occur for only 11% of the total period.

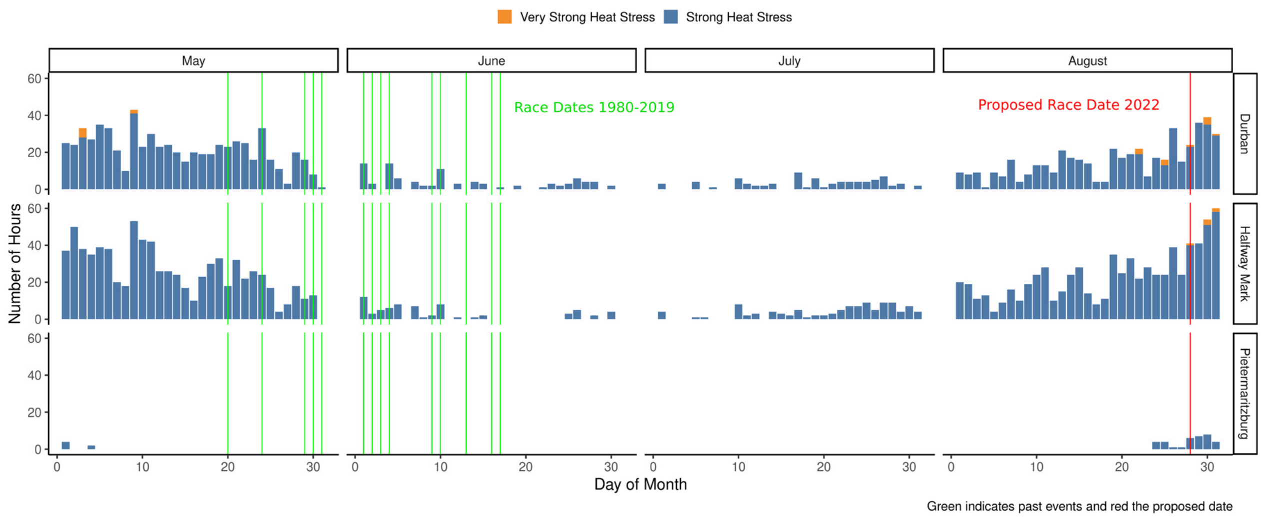


**Figure 3:** Cumulative hours of historical heat stress occurrences, per day, from the beginning of May to end of August (1980–2021).

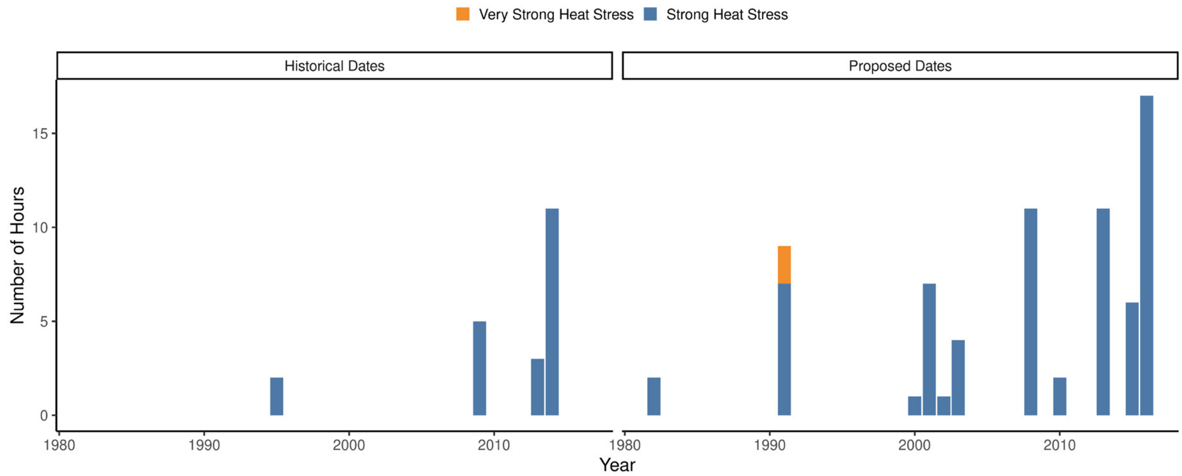


**Figure 4:** The distribution of heat stress hours, accumulated along all three reference points, for past events and the proposed event date.

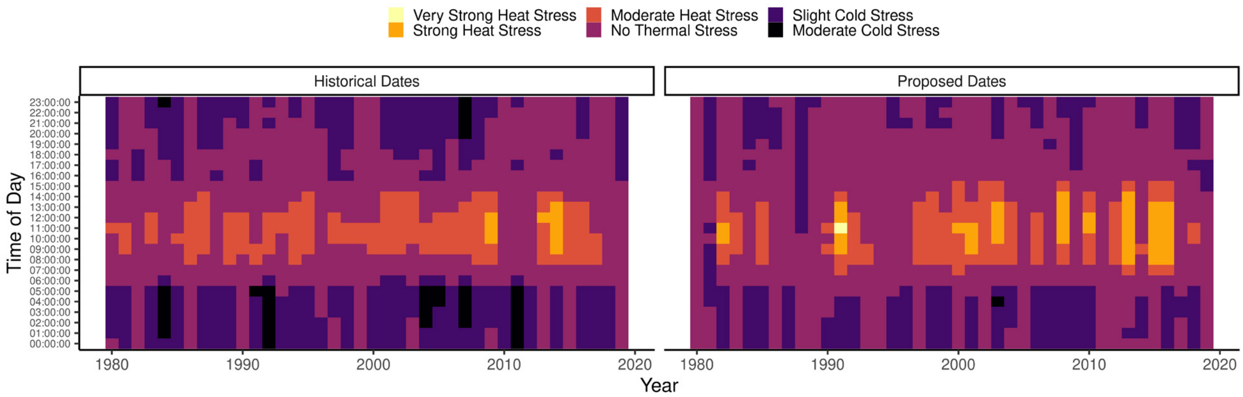


**Figure 5:** The mean Universal Thermal Comfort Index values for past events and for the proposed date, along the Comrades route.

a result of anthropogenic climate change, in line with projections for the region.[18,19] Between 2010 and 2019, 4 years had periods of heat stress on 28 August, compared to 2 years for the same period during the events before 2010. Although ‘strong’ and ‘very strong’ heat stress periods occur less frequently than ‘moderate heat stress’ periods (Figure 5), the impact of these ‘extreme periods’ to the health and performance of runners increases substantially during exposure to values above 28. According to Hollander et al.[12], the risk of heat-related illness doubles for endurance athletes when the UTCI increases from <25 to >35. Even a short exposure to these conditions should be avoided to minimise the risk of heat-related illness. These heat stress periods are especially prevalent at the reference points of Durban and the halfway mark, and between 12:00 and 14:00, as 69% of ‘strong’ heat stress periods and 80% of ‘very strong’ heat stress periods were observed during this period. Historically, the maximum heat stress period is observed at 13:00, and for the proposed date at 14:00.

In 2003, the race cut-off was extended by an hour from 11 to 12 hours. An analysis of Comrades results from 2003 to 2019 indicates that 78% of runners are on the route longer than 9 hours. Under severe conditions, runners who compete for more than 9 hours can be exposed to >5 hours of heat stress conditions. Researchers and medical-related professionals caught a glimpse of the possible consequences of ‘stronger’ heat stress periods during the 2013 Comrades Marathon event when only 55% of starters finished the race. Organisers described the weather conditions of this event as ‘very hot with a hot gusting wind the entire day’[2]. Recent studies on participants of the 2019 World Athletics Championship held in Doha, Qatar and the 2018 London Marathon indicated that endurance athletes experienced a 20% increase in the risk of heat-related illness when exposed to high UTCI values.[11,20] Participants in these studies also experienced up to a 5% decrease in running performance for every 5 points increase in UTCI values above 22.

## Conclusion

We explored the risk of heat exposure for participants of the 2022 Comrades Marathon by analysing the UTCI climatological data of the actual event days and the proposed new race date of 28 August. In conclusion, the findings show that runners will face an increased risk of heat exposure if the event is held in August compared to June or July. The UTCI climatological data, together with the predicted associated physiological responses that athletes may experience, show that a higher frequency of heat stress periods is likely to occur in the first half of May and the second half of August. Mid-June to mid-July is the period during which the risk of exposure to heat stress during participation is the lowest. Runners should be aware of the higher risk of exertional heat illness due to the possible exposure to higher UTCI values or more unfavourable climatological conditions. Furthermore, runners should be made aware of a variety of preventative strategies which may include altered pacing, rehydration, and cooling strategies to ensure safe participation.[20] Adherence to safety recommendations will ensure that more participants successfully finish the race, that the incidence rate of heat-related illness is reduced and that better Comrades Marathon running times are achieved.

Microclimatic conditions along the route and increased radiant heat from paved roads were not considered in the analysis of the UTCI climatological data and require further investigation. Therefore, the UTCI values could probably be underestimated as the microclimatic conditions may vary along the route. Furthermore, individual tolerance to heat stress varies, which may influence the individual responses and the possible risk for heat-related illness.[8,20] However, we made use of a bioclimatic and not a physiological approach[21] to investigate the possible risk for heat-related illness. These risks will likely increase as temperature increases under future climate change scenarios.[18,19]

## Acknowledgements

The results contain the modified Copernicus Climate Change Service Information of 2021. Neither the European Commission nor ECMWF is responsible for any conjectures that were made due to analyses of the Copernicus information or data it contains.

## Competing interests

We have no competing interests to declare.

## Authors' contributions

H.H.: Conceptualisation, data collection, data analysis, data curation, writing – the initial draft. B.C., R.P.B.: Conceptualisation, data analysis, methodology, writing – the initial draft, validation. S.J.P.: Conceptualisation, methodology, writing – the initial draft, validation.

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# Corrigendum

**[Original article] Jassat W, Ozougwu L, Munshi S, Mudara C, Vika C, Arendse T, et al. The intersection of age, sex, race and socio-economic status in COVID-19 hospital admissions and deaths in South Africa. S Afr J Sci. 2022;118(5/6), Art. #13323. https://doi.org/10.17159/sajs.2022/13323**

**HOW TO CITE:**
Corrigendum: The intersection of age, sex, race and socio-economic status in COVID-19 hospital admissions and deaths in South Africa [S Afr J Sci. 2022;118(5/6), Art. #13323]. S Afr J Sci. 2022;118(7/8), Art. #13323C. https://doi.org/10.17159/sajs.2022/13323C

The following terminology was erroneously reported: “non-white race” should be “people of colour”, or “black African, coloured and people of Indian descent”.

The error appears in the following instances:
Page 1, abstract, line 1 and 14
Page 1, under Introduction, paragraph 2, line 6
Page 11, under ‘Higher risk of mortality among non-white patients’, column 1, sub-heading
Page 11, under ‘Higher risk of mortality among non-white patients’, column 1, paragraph 1, lines 2, 5 and 9
Page 11, under ‘Higher risk of mortality among non-white patients’, column 2, paragraph 1, line 2
Page 12, under ‘Higher risk of mortality among non-white patients’, column 1, paragraph 3, line 10
Page 12, under ‘Socio-economic status’, column 1, paragraph 1, lines 1, 3, 6, 16 and 21
Page 12, under ‘Healthcare access’, column 2, paragraph 4, lines 3 and 13

# Corrigendum

**[Original article] Sieben EJJ, Procheş S, Mashau AC, Moshobane MC. The alignment of projects dealing with wetland restoration and alien control: A challenge for conservation management in South Africa. S Afr J Sci. 2022;118(1/2), Art. #11540. https://doi.org/10.17159/sajs.2022/11540**

**HOW TO CITE:**
Corrigendum: The alignment of projects dealing with wetland restoration and alien control: A challenge for conservation management in South Africa [S Afr J Sci. 2022;118(1/2), Art. #11540]. S Afr J Sci. 2022;118(7/8), Art. #11540C. https://doi.org/10.17159/sajs.2022/11540C

Errors that appear in the Discussion of the Research Article by Sieben et al. are corrected here. Dr Graham Harding (Registered PCO, Invader Plant Specialists (Pty) Ltd) is acknowledged for drawing the authors' attention to these errors.

**Page 4, right column, section '(1) The choice of herbicides', paragraph 1, lines 10–12:**

"Additionally, the pesticides that are used must be registered for use in aquatic environments by the Australian Pesticides & Veterinary Medicines Authority."

SHOULD BE REPLACED WITH:

"Additionally, the pesticides used should be registered and approved in the country of the intended use; in South Africa, this use is regulated under *Act No. 36 of 1947*."

**Page 4, right column, section '(1) The choice of herbicides', paragraph 3, lines 1–2:**

"Currently in South Africa there are no registered herbicides for use to control *Paspalum dilatatum* in terrestrial wetlands."

SHOULD BE REPLACED WITH:

"In South Africa, there are no herbicides registered for use to control *Paspalum dilatatum* in terrestrial wetlands specifically, although Fusilade Forte® (fluazifop-p-butyl) is registered for control of *Paspalum dilatatum* in crop fields."