Treatment technology for brewery wastewater in a water-scarce country: A review

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Water is a scarce resource in many parts of the world; consequently the application of innovative strategies to treat wastewater for reuse is a priority. The brewery industry is one of the largest industrial users of water, but its effluent is characterised by high levels of organic contaminants which require remediation before reuse. Various conventional treatment methods such as anaerobic and aerobic systems, which are effective options because of their high removal efficiencies, are discussed in this study. Other methods such as membrane based technologies, carbon nanotubes, activated carbon, electrochemical methods, algal ponds and constructed wetlands are also analysed. Their efficiency as well as advantages and disadvantages are highlighted and evaluated. Combinations of various treatment processes to improve the quality of the final effluent are discussed.

Introduction

The availability of usable fresh water is a worldwide concern, but it is especially important for countries like South Africa that have both limited water resources and a steadily growing population. According to the Strategic Water Partners Network, South Africa, by the year 2030 the demand for fresh water in South Africa will exceed supply by 17% because of population growth, rapid industrialisation, mechanisation and urbanisation.[1]

For such countries, it is extremely important to develop means for reducing water consumption by industries such as the brewing industry. The production of beer on a commercial scale requires much more water than just what is contained in the beer itself if one takes into account the water used for cooling and hygienic purposes. Brewery effluent is loaded with high levels of organic matter, nutrients and solids, as shown in Table 1, which are not easy to remove using traditional methods.

An example of a brewing company that is making an effort to minimise the water requirements of the beer production process is the South African Breweries, which is now the world's second-largest beer producer after merging with Miller Brewing of the USA to become SABMiller. However, it is a very challenging task because of the high consumption of water recorded during beer production. The average usage by the SABMiller Group is reported to be around 4.6 L of water per 1 L of beer.[3] This implies that the amount of effluent discharged is greater than the amount of beer produced. SABMiller achieved absolute water reduction of 28% between 2008 and 2015 despite volume growth.[3,4]

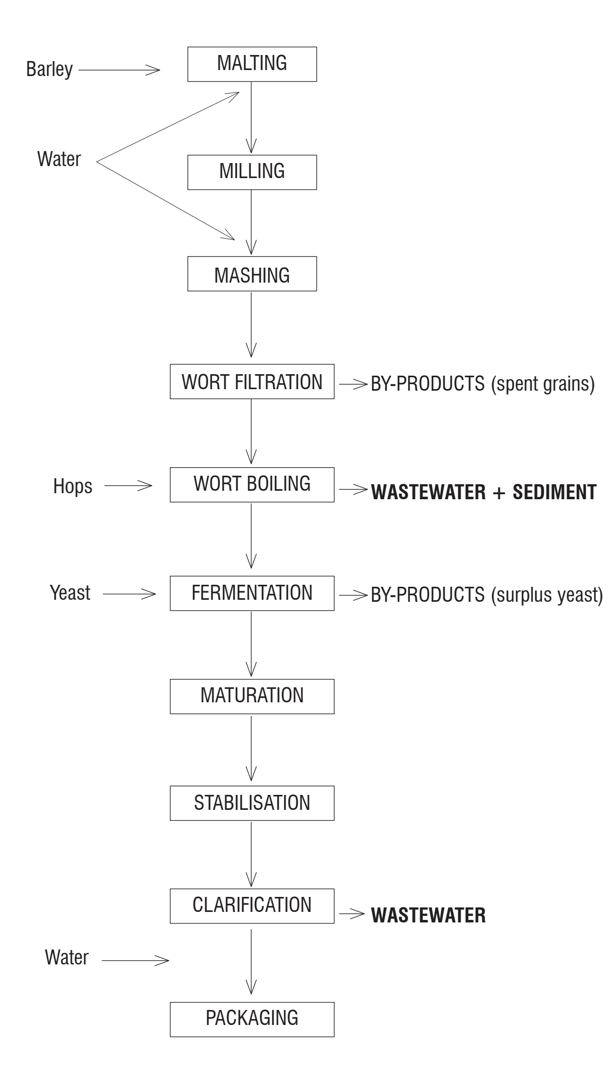
The treatment of effluent for reuse is the preferred and most widely supported methodology. Wastewater from brewery operations has a high nutrient concentration and the traditional method of disposal by delivering the water to a municipal sewage treatment plant is both wasteful and a source of concern for downstream recipients. In addition, treatment of wastewater by municipal treatment plants represents a very significant cost to brewery operators. Given the potential value of nutrient-rich brewery wastewater, and the need to conserve water usage, it therefore makes a great deal of sense to find other uses for the wastewater as well as a means of using less water overall.

Brewery operations generate large volumes of wastewater through a sequence of processes represented in Figure 1. This study analyses various conventional treatment methods for brewery wastewater and highlights the strengths and weaknesses of each method. The analysis describes the processes with technical details including some aspects related to costs, trends and achieved performance.

Table 1: Characteristics of brewery effluent

Parameter	Unit	Brewery effluent composition	Typical brewery benchmarks
Flow	Not determined	Not determined	2–8 hL effluent/hL beer
Chemical oxygen demand (COD)	mg/L	2000–6000	0.5–3 kg COD/hL beer
Biochemical oxygen demand (BOD)	mg/L	1200–3600	0.2–2 kg BOD/ hL beer
Total suspended solids (TSS)	mg/L	200–1000	0.1–0.5 kg TSS/hL beer
Temperature		18–40	
pH		4.5–12	
Nitrogen	mg/L	25–80	
Phosphorus	mg/L	10–50	
Heavy metals	mg/L	Very low	

Source: Adapted from Driessen and Vereijken[2]



Source: Adapted from Varnam and Sutherland[5]

Figure 1: Technological processes in brewery operations

Analysis of various treatment processes

Generally, the commercial beer-making process goes through the chemical and biochemical stages of mashing, boiling, fermentation and maturation, as well as separation of the wort, clarification of the wort and clarification of the rough beer product.[6] It is crucial to emphasise that these processes consume water and generate effluent streams. The solid and liquid waste fractions from these various steps, especially those containing nutrients, have been the subject of much research and have focused on either generation of revenue or at least a reduction in the cost of disposal. To separate treated water from saline water, the filtering aid known as Kieselguhr is used; however, it is entirely composed of mined diatomaceous earth, which is considered a hazardous waste. Hence, it carries significant costs associated with its use and disposal as waste. The disposal of mined diatomaceous earth is difficult because its weight increases as a result of entrained liquid. Thus, a methodology that would reduce the amount of entrained liquid and allow recovery of the Kieselguhr in a usable form would be beneficial with respect to brewery water consumption and the reduction of wastewater volume.

Another important consideration of brewery wastewater effluent is its chloride salt and ammonia content. According to a report from SABMiller regarding the performance of a pilot treatment plant initiated at Port Elizabeth in 2008, the majority of this effluent is only suitable for discharge into saline estuaries, because of the concentration of chlorides.[7] This factor inhibits the use of effluent for secondary purposes that are sensitive to salt, such as agricultural/horticultural or even reuse in the brewing industry. Historically, brewery wastewater treatment options have been limited. The classification of beer as a natural food product places strict obligations on its production processes, which includes restrictions on the input of reused materials such as wastewater. All inputs must meet the highest standards of food-grade materials, which would be complicated if the water originated from waste. Therefore, any process that promotes the reuse of brewery wastewater must generate water that meets the standards placed on fresh input water which is a costly and challenging obligation. Some of the available treatment options for brewery wastewater are described below.

Disposal, pre-treatment and treatment

To date, there have been few options available for the treatment of effluent from the brewery industry. The primary mode of treatment has been to simply dump the wastewater into the environment without any kind of treatment. However, this practice has the major drawback of environmental pollution. Pressure for beer production to satisfy increasing consumer demand generates large volumes of effluent. This has forced the beer brewing industry to implement a pre-treatment option before disposal. Generally, this pre-treatment aims to remove solids and reduce the pollutants in the water. Simple dumping has been replaced by disposal of the pre-treated effluent to municipal water resource recovery facilities, where it is added to the municipal wastewater stream for treatment before release into the environment. The mixture goes through a traditional municipal wastewater treatment process of primary, secondary and tertiary treatments, which are physico-chemical and biological treatments. The chemical oxygen demand (COD) of brewery wastewater is relatively high, generally between 2000 mg/L and 6000 mg/L, because of the presence of organic materials as by-products of the brewing process.[8] The presence of these materials represents the depletion of oxygen in the water that occurs through the oxidative chemical processes that break it down to carbon dioxide and water. The abundance of brewery wastewater in the municipal wastewater treatment systems increases the level of contaminants in the system thereby, adversely affecting the overall performance of the plant.

Anaerobic and aerobic treatment

The abundance of organic substances in brewery wastewater is the main cause of high COD which requires efficient treatment methods that can easily remove organic pollutants. Generally, biological methods are a more viable option than physico-chemical methods regarding the efficient removal of organic matter from wastewater. Therefore, treatment by passing the wastewater through an anaerobic digestion process using anaerobic bacteria and then through an aerobic process using 'activated sludge' has become the standard and most recommended process for brewery effluent. Both anaerobic and aerobic methods are widely used today, aiming to reduce the COD of brewery effluent before it is transported to municipal water resource recovery facilities.

Haydon[9] indicated that anaerobic digestion of brewery effluent is increasingly being utilised to generate an energy source such as biogas. This requires the hydrogen sulfide content of the biogas to be scrubbed out. The generated biogas can be used to maintain the operating temperature of the anaerobic digestion system or to generate revenue. As shown in Table 2, aerobic systems are more efficient in terms of removal of organic pollutants but require the use of oxygen which increases operating and capital costs. Both anaerobic and aerobic processes require high capital costs, however, they differ on operating costs which are lower for anaerobic compared to aerobic processes. The start-up cost of anaerobic digestion is high because of the laborious seeding process required for an appropriate culture of microorganisms and anaerobic processes are unable to efficiently reduce the level of some nutrients such as nitrates.

In the search for efficient brewery effluent treatment methods, the treatment of brewery effluents has been able to draw from the experience of other applications and industries, particularly the treatment of acid rock drainage through the use of aerobic and anaerobic digestion structures.

Table 2: Comparison between anaerobic and aerobic systems

	Anaerobic	Aerobic
C Chemical oxygen demand removal	65–90%	90–98%
Energy production	High: CH_4 is produced as biogas	Low: only CO_2 released
Energy consumption	Low	High
Sludge production	Low: high solid retention	High
Nutrients (N/P) removal	Low	High
Space requirement	Low	High
Discontinuous operation	Easy	Challenging

Source: Adapted from Driessen and Vereijken[2]

Aerobic digestion structures are typically wetlands and shallow settling ponds that provide an oxidative environment for entrained contaminants, while anaerobic digestion structures use anaerobic bacteria to digest many of the nutrients that are found in brewery wastewater. These methods are separate from the anaerobic digestion and activated sludge processes used to treat brewery wastewater.

Cowan and Rende,[10] discusses the generation and use of biogas as a self-supporting aspect of the Integrated Algae Ponding System. This system uses both anaerobic and aerobic processes in a deep fermentation pit. In the lower section of the pit, anaerobic digestion consumes organic matter in wastewater. The odoriferous materials are oxidised through consumption by aerobic algae, driven by solar input, in the upper section of the pit. Similar to other systems, it is common practice in this system to include a fish farming operation at the last stage of the process before release into the environment. The fish farm is added as a means of 'polishing' the effluent water, as the fish consume any remaining algae. This aspect of the process is problematic for the South African brewing industry, as suitable indigenous fish species have not been identified. Also, the number of the fish farms that have been set up reduced quickly as people took advantage of the novel source of food. Consequently, the quality of effluent discharged into the environment is not as 'polished' as might be expected.

High rate algal ponds and constructed wetlands treatment

Jones et al.[11] completed a study on SABMiller's Eden Project carried out at its Ibhayi brewery location. This was an experimental facility aiming at testing and adapting the remediation of brewery wastewater using high rate algal ponds and constructed wetlands (HIRAP/CW) technology. The experimental station used a specially designed greenhouse to test the use of the treated effluent for its suitability in secondary applications. These experiments sought to reduce or eliminate the chloride content of the wastewater. The treated effluent proved to be suitable for the growth of vegetables hydroponically, as well as for raising fish. Additionally, sodium tolerant crops such as bananas were grown successfully with the treated effluent. The SAB Miller project needs to be expanded in such a way that all effluent from the Ibhayi brewery and SAB Miller's other locations can be treated in a similar manner.

The SAB Miller experiment is unique and represents the first case study of a commercial brewery treating brewery effluent in South Africa. The method proved to be effective in reducing both ammonia and phosphate levels in the effluent water to regulated standards. However, the method is unable to remove chlorides and sodium salts from the effluent. Hence, the effluent remains only suitable for discharge into a saline estuary. The advantage of this technology is its extremely low cost and reliability. The technology is adapted from the remediation of acid mine drainage and uses both a bacterial phase to reduce organic components in the wastewater and an aerobic algal pond phase to consume mineral components such as phosphates. Kivaisi[12] and Shrestha et al.[13] examined the use of constructed wetlands (CW) technology for the reduction of COD in the treatment of municipal wastewater. They reported that it could be reduced by 90–94% by a 'mature' wetland. Similarly, Shepherd et al.[14] examined the use of CW technology in the treatment of winery wastewater, which is similar to brewery wastewater, and reported a COD removal efficiency of up to 98%. All this evidence showed that the application of HIRAP/CW technology for the treatment of brewery effluent could be eminently successful for reducing COD in effluent before passing it to further treatment or to the environment. However, as mentioned earlier, the saline content of the effluent was unaffected by HIRAP/CW treatment.

Carbon nanotubes based treatment

Simate[15] used carbon nanotubes to treat effluent from the brewing industry. The carbon nanotubes were prepared from carbon dioxide (CO_2), which is another important by-product of the beer brewing industry. The nanotubes were found to be very effective as a flocculating agent and as a granular filtration medium during treatment. It was reported that treatment using carbon nanotubes reduced the turbidity of the effluent to less than 5 NTU and removed 96.% of the effluent COD. Given the current attention to carbon nanotubes/graphene technology, this is a promising alternative for the treatment of brewery effluents in the near future. The strength of this technology is the fact that carbon nanotubes can be produced from purified CO_2 as a carbon source. Furthermore, it is a possible means of using up large amounts of the CO_2 produced by the brewing industry from the fermentation process. Therefore, this could contribute to the attenuation of global warming effects from the brewing industry. However, carbon nanotube treatment for effluent from the brewing industry is not yet a viable option. The technology requires large amounts of energy for CO_2 purification and carbon nanotube synthesis. Therefore, the costs of scaling up to a commercial treatment operation would be exorbitant. Also, the unavoidable release of carbon nanotubes into the environment might result in massive environmental and health effects with unexpected consequences. Carbon nanotubes and other fullerene-type compounds are naturally occurring products in soot from carbon combustion, while graphene is the basic molecular building block of graphite and coal. The challenge with this carbon nanotubes technology is the fact that the environment has never been exposed to it on a large scale. For this reason, more investigations are required on capital and operating costs as well as environmental impact and process safety of carbon nanotubes.

Advanced oxidation treatment process

Advanced oxidation treatment processes (AOP) are widely used in wastewater treatment, especially in alcohol distilleries, which generate almost the same type of effluent as the brewing industry, with high levels of organic compounds. The production process in distilleries is almost same as breweries because they both involve fermentation.[16] Ozone, hydrogen peroxide and ultraviolet irradiation are used to produce hydroxyl radicals (•OH) during the first stage of the oxidation. In the second stage, hydroxyl radicals (•OH) react with organic contaminants to produce precipitates. Established AOP technologies can be made possible with the help of the following combinations: ozone/hydrogen peroxide (O_3/H_2O_2), ozone/ultraviolet irradiation (O_3/UV) and hydrogen peroxide/ultraviolet irradiation (H_2O_2/UV).[17] Bes-Piá[17] revealed that both ozone and hydroxyl radicals (•OH) are strong oxidants and are capable of oxidising a number of organic compounds. Ozone is a powerful oxidant that reacts with a great number of organic compounds and facilitates the removal of organic pollutants from wastewater, once dissolved in water. It acts in two different ways, (1) by direct oxidation as molecular ozone and (2) by indirect reaction through formation of secondary oxidants like free radical species, particularly the hydroxyl radicals (•OH).

Pala and Erden[18] reported another AOP process known as Fenton's oxidation using Fenton's reagent, which is a mixture of hydrogen peroxide and iron salts (Fe^{2+} or Fe^{3+}). This technology is based on the production of hydroxyl radicals (•OH) that ultimately leads to precipitation or decolourisation of the effluent.[18] Furthermore, Fenton produces homogeneous reaction and is environmentally friendly.[18] There are other AOP processes such as catalytic oxidation using the combination of TiO_2/UV, catalytic ozonation and boron doped diamond electrodes; however, they are still only on a laboratory scale. Oxidation processes show a promising future for their application in many wastewater treatment projects. They are emerging technologies with great potential to remove pollutants from many types of wastewater including brewery effluent. These processes utilise the strong oxidising power of hydroxyl radicals to oxidise organic compounds to the preferred end products of carbon dioxide and water. However, sometimes they can be costly because supplementary treatment may be necessary to remove ozone. In addition, there is a problem of turbidity/NO_3 interference to resolve.

Membrane filtration treatment

Membrane filtration can be an effective treatment depending on the type of effluent. This method can achieve up to 99% COD, Biochemical oxygen demand (BOD), and total suspended solids (TSS) removal. If the required final product is potable water, reverse osmosis can be added to the process. Microfiltration (MF), Ultrafiltration (UF) and Nanofiltration (NF) membranes have been used successfully to remediate brewery effluent.[4,19,20] The challenge with membrane technologies is fouling and energy consumption, but new types of membranes with anti-fouling properties make the membrane process a viable treatment option. More studies are required in this area to produce membranes that can work with minimum fouling and efficient use of energy. Conversely, membrane technologies should only be used as a polishing step after a pre-treatment option involving anaerobic or aerobic processes or a combined anaerobic/aerobic process.

Daufin et al.[21] reported that in the brewery industry, cross-flow or dynamic filtration can play a significant role that can be a technological alternative to the conventional solid and liquid separations. The efficiency of this method depends on two factors (1) the recovery of extract during the wort clarification, and (2) beer recovery from tank bottoms, more especially fermentation and maturation vessels.[21] Currently, tank bottom recovery is reported to be the principal membrane application in brewing.[21] MF can be utilised for three purposes: mash separation, clarification of rough beer and cold sterilisation of clarified beer before conditioning. UF and NF are suggested for effluent treatment; however, this does not exclude pre-treatment processes. It is important to note that industrial applications are more focused on the clarification of rough beer and sterile filtration of clarified beer.

Membrane bioreactor treatment

Membrane bioreactor (MBR) treatment is a successful technology for wastewater treatment and during the last decade has also produced successful results for drinking water.[22,23] It is a combination of two proven technologies: enhanced biological treatment using activated sludge or an anaerobic unit, and membrane filtration. The development of various combinations of membranes with other conventional treatment components is justified by the increasing water price and continuous depletion of water resources. Therefore, MBR is seen as an economical and technically viable option for wastewater treatment.[24] An MBR system is constructed in such a way that a membrane is integrated with a bioreactor. Two MBR process configurations can be identified: side-stream and submerged. In a side-stream process, the membrane module is placed outside the reactor and the reactor mixed liquor flows over a recirculation loop containing the membrane. In a submerged configuration, the membrane is placed inside the reactor and submerged into the mixed liquor. Side-stream MBRs are more energy intensive than submerged MBRs because of high operational transmembrane pressures and the significant volumetric flow required to achieve the desired cross flow velocity.[25,26] Submerged MBRs use more membrane area and operate at lower flux levels.[25]

Dai et al.[27] reported that MBR technology can be applied successfully to brewery wastewater treatment and showed COD removal of up to 96% using an upflow anaerobic sludge blanket (UASB) reactor with an integrated membrane. Brewery effluent treatment using MBR was also reported in other studies.[28,29,30] In most of these studies, significant amounts of COD removal of up to 90% were recorded which indicates that the MBR process can be a successful option for the treatment and reuse of brewery effluent. However, as with any membrane process, fouling is the greatest challenge and needs to be managed with routine cleaning and maintenance. Energy consumption can also be a weakness especially when it comes to side stream membranes. Capital costs can also be higher because of the combination of two units: membrane, and anaerobic or aerobic reactor.

Microalgae based treatment

Mata et al.[31] analysed the potential of using a microalgae strain known as *Scenedesmus obliquus* for brewery effluent treatment. Usually, microalgae can grow in the brewery effluent using contaminants as nutrients. According to Mata et al.[31], the best operating conditions are aerated cultures exposed to high intensity light for 12 h daily. It was reported that maximum biomass growth was achieved after 9 days with an output of 0.9 g of dry biomass per litre of culture. Removal of contaminants with 57.5% COD and 20.8% total N_2 was recorded after 14 days. The final values of COD and total nitrogen were found to be 1692 mg O_2L and 47 mg N_2/L respectively. Compared to discharge standards, which are 150 mg O_2/L and 15 mg N_2/IL, respectively, final values of COD and total nitrogen were higher. As a result, wastewater treatment by microalgae can be achieved in either the secondary or a tertiary phase of the treatment, combined with other treatments. Membrane technologies can easily be added, in this case, for the polishing step. After utilisation, the resulting algal biomass can be collected and used for biofuel production. Algae treatment for wastewater is an emerging method that can also help to solve the challenge of brewery effluent treatment at lower costs. More investigations are required to find suitable strains that are able to efficiently remove large amounts of organic contaminants from brewery effluents, but there is a potential and promising future regarding this type of treatment.

Treatment using air cathode microbial fuel cells

Feng et al.[32] examined the efficiency of a microbial fuel cell (MFC) method to determine its suitability for brewery effluent treatment. This method is still new and has drawn worldwide interest because it can generate electricity from organic matter present in wastewater. MFCs are devices that use microorganisms to convert chemical energy into electricity from organic matter. MFC is a combined system with anaerobic and aerobic characteristics. Anaerobic digestion by microorganisms takes place in the solution close to the anode with the cathode exposed to the oxygen. Electrons released by bacterial oxidation of organic compounds are transferred to the cathode where they react with oxygen from water. Furthermore, Feng et al.[32] reported that the effectiveness of MFC treatment would require a good understanding of how solution chemistry and operational parameters affect the efficiency of the treatment. Feng et al.[32] used parameters such as maximum power densities and COD removal as functions of temperature, effluent strength, and coulombic efficiencies (CE) to test the efficiency of MFC. It was found that when temperature was decreased from 30 °C to 20 °C, the maximum power density was reduced from 205 mW/m^2 to 170 mW/m^2. However, COD removals and CE decreased slightly with temperature decrease. Also, the performance of the reactor was strongly affected by the buffering capacity. Power density was significantly increased by 136% with the addition of 50 mM phosphate. COD removal efficiency was 85% and 87% at 20 °C and 30 °C, respectively. Performance of sequential anode-cathode MFC achieved

COD removal efficiency of more than 90%. In another study, Mathuriya et al.[33] achieved a COD removal of up to 94% using the MFC method for brewery wastewater. In conclusion, MFC more specially the sequential anode-cathode, can provide a new approach for brewery wastewater treatment while offering an alternative method of generating energy.

Activated carbon based treatment

Activated carbon is one of the most powerful adsorbents for removing a wide range of contaminants from industrial and municipal wastewater, landfill leachate and contaminated groundwater. This powerful adsorbent can cope with a wide range of contaminants including organic contaminants present in brewery effluent. Different contaminants may be present in the same discharge and carbon may be used to treat the total flow, or it may be utilised to remove specific contaminants as part of a multistage approach.[8] Brewery effluent is characterised by its distinctive odour resulting from fermentation and other beer-making processes and it may also contain carbon-sulfur bonds. Molecules with carbon-sulfur bonds and aromatic rings often smell and produce a bad taste, but these are molecules preferentially adsorbed on carbon. Carbon's de-chlorinating capability results from its ability to act as a reducing agent that reacts with strong oxidising agents such as chlorine dioxide and hypochlorous acid. Carbon adsorption is used in the brewing process to treat tannic acid for odour removal.[8] Carbon is also used to remove colour from malts for use in clear beers and other flavoured malt beverages. Activated carbons are an effective treatment option to assure that treated water is taste and smell free. It is the least expensive process and does not require electricity or high water pressure. It reduces a wide variety of organic contaminants and can be designed to reduce levels of some inorganic chemicals like lead and arsenic. However, activated carbon is ineffective against many inorganic contaminants such salts, iron, fluoride, aluminium and calcium.[8]

Treatment of brewery effluent using electrochemical methods

The electrochemical method of wastewater treatment was first used to treat sewage generated on board ships.[34] Later, the application of electrochemical treatment was widely used in industrial wastewater treatment that is rich in refractory organics and chloride content.[35] Vijayaraghavan et al.[36] developed a novel brewery wastewater treatment method based on in situ hypochlorous acid generation. The generated hypochlorous acid served as an oxidising agent that destroyed organic compounds present in the brewery wastewater. COD removal of up to 97% was achieved in this study. The hypochlorous acid was generated using a graphite anode and stainless steel sheet as a cathode in an undivided electrolytic reactor. Initially, during electrolysis, chlorine was produced at the anode and hydrogen gas at the cathode. This method is appropriate for the degradation of biorefractory organic contaminants because complete or partial decomposition of organic substances is achievable. The advantage of electrochemical methods is that they require less hydraulic retention time and are not subject to failure resulting from variation in wastewater strength or the presence of toxic substances.

Non-thermal quenched plasma technology treatment

Plasma usually results from the increased energy of a gas provided by various sources, such as electric, magnetic, shock waves, ultrasound, thermal and optical (laser) sources.[37] Plasma is a highly ionised gas that occurs at high temperatures and is considered as a fourth state of matter because intermolecular forces created by ionic attractions and repulsions give these compositions distinct properties.[38] Plasma is similar to gas in terms of physical properties as it does not have fixed shape or volume. However, it differs from gas by being able to form structures such as filaments, beams and double layers under the influence of a magnetic field. Doubla et al.[39] demonstrated the use of this technology for the treatment of brewery effluent.[39] Humid air plasma created by an electric gliding arc discharged in humid air was used during the experiment and contributed to the removal of organic pollutants from brewery effluent. The gliding arc discharge in humid air was able to produce •NO and •OH radicals with strong oxidising characteristics. The •OH radical is a very powerful oxidising agent that is responsible for oxidation reactions with organic contaminants considered as targets during treatment. The study recorded BOD removal efficiencies of 74% and 98%. The technology is also effective in the neutralisation process of alkaline effluents because of the pH lowering effect of the plasma treatment originating from the production of nitrate ions. This method can be combined with biological treatments to further remove organic pollutants easily and quickly to an acceptable level for effluent reuse.[39] Although high removal efficiencies can be achieved, the method is expensive because of the high energy requirements of the gas and energy sources such as laser. If combined with biological treatment as mentioned earlier, capital and operating costs will increase.

Discussion

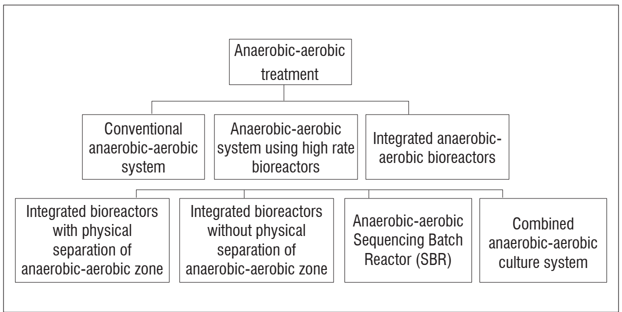
Brewery effluent still needs efficient solutions for remediation that are low cost. Table 3 shows the performance of the various methods discussed in this study in terms of COD removal. These methods show promise but each have weaknesses that need to be addressed for a better outcome. As the demand for beer and other brewery products increases, so does the amount of generated effluent. The brewing industry is focused on producing more beer but most brewers are ignoring the optimisation of water used in the process and the development of an efficient treatment for the generated effluent. Generally, brewery effluent is simply dumped into the nearest municipal water treatment plant for processing along with sewage and other wastes.

Table 3: Methods used for the treatment of brewery effluent and the efficient removal of chemical oxygen demands

Process	COD removal %
Quenched plasma	74–98[39]
Upflow anaerobic sludge blanket reactor	73–91[40]
Aerobic reactor	90–98[2]
Combined bioreactor	98
Membrane bioreactor	96[27]
Electrochemical method	97[34]
Microbial fuel cells	94[41]
Nanofiltration	96[20]
Reverse osmosis	100[42]

Source: Adapted from Simate et al.[8]

Some efforts have been made in the recovery of economic value from the solid organic residues of the brewing industry, such as the sale of malting and yeast residues for incorporation into animal feedstock. However, these efforts do not have any impact on water consumption and wastewater remediation in the brewery environment. According to Haydon[9], the brewing industry has long been aware of possible uses for brewery effluents, such as the generation of biogas, but has not pursued this option to date because of their lack of economic viability. However, this appears to be changing as the rising costs of input resources make utilisation of by-products economically more feasible. The biggest challenge for the brewing industry remains the volume of wastewater that it produces. Shepherd[14] reported that the consumption of water by brewing industry is almost 10 L per 1 L of beer, which is double the figure reported in the study by Fillaudeau et al.[6] An efficient brewery should use between 4 L and 7 L of water to produce 1 L of beer.[43] Kanagachandran[44] estimated that about 3–10 L of effluent is produced per 1 L of beer produced in breweries. These figures stress the importance of reducing effluent volumes in the industry and also imply that the quantity of generated brewery effluent will depend on the management of the production process. More studies need to be undertaken to optimise the use of water in the brewing industry to reduce the amount of effluent generated during production. The brewery effluent is rich in nutrients, which represent a resource that could be developed into a valuable commodity. For example, The Eden Project undertaken by SABMiller pointed the way to remediation of brewery effluent that could lead to its complete reuse within the brewing industry.[45] Complete reuse would cut the water requirements of the brewing industry by a huge amount, given that 70% of water used by the industry is lost as waste. In one of SABMiller's breweries, this would amount to the recovery of 7 million m^3 (7 billion litres) from one single brewery plant per year. The obstacle that needs to be overcome in these efforts is the generation of an effluent that is eventually close in quality to the water used as an input stream into the brewing process. To reach that stage, the nutrient and the mineral content must be reduced. Particularly salts, ammonia, phosphate and other inorganic materials must be reduced to below those of the input water. At the present state, the effluent contains high levels of salts, which renders it not viable for use in secondary purposes. Despite the fact that algal pond treatment of brewery effluent is an acceptable start, there is still room for new methods. Further improvements are required to implement treatment methods other than anaerobic digestion and algal ponds, possibly a combined aerobic and anaerobic system could be a suitable option as illustrated in Figure 2.[46]



Source: Driessen et al.[46]

Figure 2: Combined aerobic and anaerobic systems used in the treatment of wastewater.

Figure 2 shows that there are basically four types of integrated aerobic-anaerobic bioreactors and the properties of these integrated bioreactors as outlined by Driessen et al.[46] are: (1) most of the COD (70%–85%) from the anaerobic reactor is converted into biogas, (2) almost 98% of the COD and nutrients are removed in the anoxic/aerobic post-treatment stage. The advantages of these combined treatment technologies over aerobic conventional treatment processes is that there is a reduction in the production of sludge (bio), less space is required and a positive energy balance is maintained.[2] Recently, the combination of tall and slender internal circulation anaerobic reactors with airlift reactors (aerobic reactors) has resulted in the design of well compacted effluent treatment plants that meet the required surface water quality.[2] With this method it is possible to successfully treat brewery effluent, as illustrated in Table 3, which shows that recorded COD removals are between 73% and 100%. These values are very high and there is no questioning their effectiveness when looking at the methodological approach and equipment used to achieve such results. Some methods are suitable for pre-treatment and others can be used as a polishing step. This supports the option of combining processes to achieve the high quality required for rendering effluent suitable for reuse in the brewing process. However, in these studies, the economic aspects are not always meticulously analysed, which makes it difficult to confirm with certainty if a method or a combination of methods would be economically viable for treating brewery effluent. There is an absence of adequate economic analysis on operating and capital costs to help make an effective choice for treatment, especially when dealing with large volumes of effluent.

Conclusions and recommendations

Researchers must continue to discover effective ways to reduce the amount of brewery effluent that is produced annually. Improvements must be found to recover brewery effluent as much as possible so that it can be reused. Water scarce countries like South Africa, and its brewing industry, face a crisis of clean water availability. While new technologies such as the application of carbon nanotubes appear to have the potential to achieve highly desirable results in laboratory tests, the technology is not even close to being ready for application in the brewery industry and would be enormously expensive on a large scale. In addition, there are the unidentified health risks of carbon nanotubes presence in the environment. Similarly, the 'low technology' approach for remediation is not capable of achieving the desired results. Biological methods such as aerobic and anaerobic treatments are widely used because of their capacity to remove organic contaminants, achieving high COD removal, but are characterised by high capital or operating costs. These methods are used as pre-treatment options and further treatments may be required.

This review has shown some promising results from MBR, quenched plasma, MFC and the electrochemical method. There is a great potential in these methods; however, the technology costs resulting from energy consumption and maintenance may be inhibitory. The Algal ponds and constructed wetland method is reliable and has the advantage of lower costs. This method shows effectiveness in the removal of ammonia and phosphates but it is unable to remove chlorides and sodium salts. Membrane filtration is being used for industrial wastewater treatment including brewery effluent. Membrane technology has found application in drinking water and wastewater reuse and has undergone rapid development and improvement in quality and costs over the last decade, and could be used as a polishing step after pre-treatment options. Activated carbon based treatment methods can be an appropriate treatment option for the brewery industry. It is a cheap option that could easily allow the removal of organic contaminants from brewery effluents. However, it may be challenged by health and environmental concerns related to the use of carbon or coal for the treatment of large amounts of effluent.

The integration of technologies or processes can also be an option to improve the quality of the final product. This option needs more investigation, especially regarding operating and capital costs including energy consumption, maintenance, process efficiency, water consumption and optimisation. It is incumbent upon the brewery industry to invest in developing alternatives for treatment of brewery effluent, looking at the effluent as a commodity resource rather than as waste. Breweries around the world would do well to form a research consortium to address the problem of brewery wastewater, its remediation and reuse. While the largest breweries are located in the wealthiest economic regions of the world, they do not face the eventual water shortages of less water-affluent countries like South Africa. The growth of breweries in developing countries demands that water conservation and remediation methods in the brewery industry be developed sooner rather than later. It is further recommended that a thorough or a more detailed cost analysis of the various treatment processes in this review be carried out to help determine the most cost-effective way to treat wastewater from breweries.

Authors' Contributions

The authors worked together from topic development, collection of information, discussion, critical analyses, writing of the manuscript up to the final corrections. The article is a result of synergy of both authors.

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