https://dx.doi.org/10.4314/dujopas.v9i2a.21
ISSN (Print): 2476-8316
ISSN (Online): 2635-3490
Dutse Journal of Pure and Applied Sciences (DUJOPAS), *Vol. 9 No. 2a June 2023*

Mitigating Rubber Waste Effluent Through Microbial Approaches: A Review

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Abstract
This review discusses the progress made in the remediation of rubber waste effluent using microbial techniques. Rubber processing facilities generate wastewater containing various pollutants, such as organic compounds, that are harmful to the environment. Microbial techniques, such as bioremediation, have been developed as a sustainable solution to treat these effluents. This article highlights the recent advancements made in this field, including the use of trickling filter systems and microbial fuel cells. These methods have been found to be effective in removing various pollutants, including phenols and formaldehyde. Furthermore, research has shown that these techniques are environmentally friendly, low-cost, and sustainable options for the treatment of rubber waste effluent. The article concludes that microbial techniques are a promising alternative to conventional treatment methods and should be further developed and explored for the treatment of rubber waste effluent.

Introduction
Pollution is a growing concern that poses significant threats to the environment, ecosystems, and human health (Ifijen *et al*., 2020; Ikhuoria *et al*., 2020). It refers to the introduction of harmful substances or contaminants into the natural environment, resulting in adverse effects on living organisms and the overall balance of ecosystems (Ifijen *et al.*, 2022; Ize-Iyamua *et al.*, 2019). Rubber waste effluents, which are generated from the production and processing of rubber products, can have significant negative impacts on the environment if not properly treated (Al-Musawi *et al.,* 2019). One effective method for treating rubber waste effluents is the use of microbial treatment (Saha *et al.,* 2018; Swaminathan & Rengasamy, 2015).

Microbial treatment involves the use of microorganisms, such as bacteria or fungi, to break down the organic pollutants present in the waste effluent (Environmental Protection Agency, 2019). These microorganisms utilize the pollutants as a source of energy and convert them into simpler, less harmful compounds. Microbial treatment can be conducted in a number of ways, including aerobic and anaerobic treatment, as well as bioreactors (Environmental Protection Agency, 2019).

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Aerobic treatment involves the use of oxygen to support the growth of aerobic microorganisms that break down organic pollutants. This method is typically used for the treatment of rubber waste effluents that contain high concentrations of organic pollutants, such as rubber oils and solvents Al-Musawi *et al.,* 2019). Anaerobic treatment, on the other hand, does not require oxygen and relies on the use of anaerobic microorganisms that can break down organic pollutants in the absence of oxygen. This method is typically used for the treatment of rubber waste effluents that contain high concentrations of organic compounds, such as latex and natural rubber Al-Musawi *et al.,* 2019).

Bioreactors are a type of microbial treatment system that provide a controlled environment for the growth of microorganisms (Saha *et al.,* 2018). Bioreactors can be designed to facilitate either aerobic or anaerobic treatment, depending on the specific requirements of the rubber waste effluent being treated (Saha *et al.,* 2018). Bioreactors are particularly effective for the treatment of high-strength waste effluents, as they provide a large surface area for the attachment of microorganisms and can be operated under controlled conditions to optimize treatment efficiency.

Overall, the use of microbial treatment methods for treating rubber waste effluents offers a number of advantages (Swaminathan & Rengasamy, 2015). Microbial treatment is a cost-effective and environmentally friendly method for the treatment of rubber waste effluents, as it does not require the use of harsh chemicals or other expensive treatment processes (Swaminathan & Rengasamy, 2015). Additionally, microbial treatment can be tailored to the specific requirements of the waste effluent being treated, making it a versatile treatment method that can be applied to a wide range of rubber waste effluents. Thus, this review conducted a comprehensive examination of recent research studies that have employed a microbial approach to treat effluent from rubber waste.

The Benefits of Utilizing a Microbial Method to Treat Effluents from Rubber Waste in Comparison to Alternative Methods

There are several advantages of treating rubber waste effluents using a microbial approach over other approaches (Al-Musawi *et al.,* 2019). Here are some of them:

i. Cost-effective: Microbial treatment is a cost-effective method for treating rubber waste effluents compared to other conventional methods. It requires less capital investment and operating costs, making it an ideal solution for industries that want to reduce their waste management costs.
ii. Environmentally friendly: Microbial treatment is an environmentally friendly approach that utilizes microorganisms to degrade organic pollutants in the effluents. Unlike other treatment methods, microbial treatment does not produce any harmful byproducts or residues.
iii. High efficiency: Microbial treatment is a highly efficient method for treating rubber waste effluents. The microorganisms used in the treatment process are capable of degrading a wide range of pollutants, including toxic chemicals and heavy metals.
iv. Versatility: Microbial treatment can be used to treat different types of rubber waste effluents, including wastewater, sludge, and solid waste. This versatility makes it a useful approach for industries that produce different types of rubber waste.
v. Minimal maintenance: Microbial treatment requires minimal maintenance and can be easily integrated into existing wastewater treatment systems. It also has a low energy consumption, making it an energy-efficient approach.

Overall, microbial treatment is a cost-effective, environmentally friendly, and highly efficient method for treating rubber waste effluents, and its versatility and minimal maintenance make it an attractive option for industries seeking to manage their waste more effectively.
There are several types of microbial treatment methods that can be used to treat rubber effluent, including:

Activated sludge process
The treatment of rubber waste effluent using the activated sludge process involves the application of a biological treatment method to remove pollutants from wastewater generated during rubber processing (Koul *et al.,* 2022). This process has been widely used in various industries, including the rubber industry, due to its effectiveness in reducing organic compounds and other contaminants (Zheng *et al.,* 2013).

The activated sludge process is a biological wastewater treatment method that utilizes microorganisms to degrade organic matter in the presence of oxygen. The process involves the introduction of wastewater into an aeration tank, where microorganisms, mainly bacteria and protozoa, consume and metabolize organic compounds present in the effluent. This microbial degradation process converts complex organic matter into simpler forms, such as carbon dioxide, water, and microbial biomass (Zheng *et al.,* 2013).

Rubber waste effluent typically contains high levels of organic compounds, such as proteins, carbohydrates, and fats, which can be effectively removed through the activated sludge process. Studies have shown that the process can achieve significant removal efficiencies for various pollutants present in rubber waste effluent (Wang *et al.*, 2018). Furthermore, the performance of the activated sludge process can be enhanced by optimizing operating parameters such as hydraulic retention time (HRT), sludge retention time (SRT), and dissolved oxygen (DO) concentration. Controlling these parameters allows for better microbial activity, resulting in improved pollutant removal efficiency.

Here are the steps involved in using the activated sludge process to treat rubber effluent (Koul *et al.,* 2022; Zheng *et al.,* 2013; Wang *et al.*, 2018):

i. Pre-treatment: Before the rubber effluent can be treated using the activated sludge process, it is important to remove any large particles or solids from the wastewater. This can be done using physical treatment methods, such as screening or sedimentation.
ii. Aeration tank: The rubber effluent is then introduced into an aeration tank, where it is mixed with activated sludge. The activated sludge is a mixture of microorganisms, such as bacteria and fungi, that feed on the organic pollutants in the wastewater.
iii. Aeration: The aeration tank is equipped with an aeration system, such as diffusers or mechanical aerators, that supply oxygen to the microorganisms in the activated sludge. The oxygen is necessary for the microorganisms to break down the organic pollutants in the wastewater.
iv. Settling tank: After the rubber effluent has been mixed with the activated sludge and aerated, it is transferred to a settling tank. In the settling tank, the activated sludge and any remaining solids settle to the bottom of the tank, while the treated wastewater is removed from the top of the tank.
v. Disinfection: Finally, the treated wastewater is disinfected using a disinfection system, such as ultraviolet (UV) light or chlorine, to kill any remaining microorganisms in the water.

In the study conducted by Wang *et al.* (2018), a combination process of anaerobic and two-stage biological contact oxidation (A/O1/O2 biofilm) was utilized for the treatment of natural rubber processing wastewater. The core technology employed in this case was biofortification, which involved the direct addition of bacterial agents and the use of biological fillers to enhance the performance of the biological treatment system. The activation of sludge played a crucial role in the overall treatment process. By adding bacterial agents and employing biological fillers, the microorganisms responsible for the degradation of organic pollutants in the wastewater were efficiently fixed and their activities were enhanced. This ensured the optimal functioning of the activated sludge process, which relies on the metabolic activity of microorganisms to degrade pollutants. Following the commissioning of this biofortification-based treatment process, the wastewater treatment system was put into operation. The results demonstrated that the related sewage discharge indicators, including pH, suspended solids (SS), ammonia nitrogen (NH3-N), chemical oxygen demand (COD), and biochemical oxygen demand (BOD5), all met the first-level standard of the "Integrated Wastewater Discharge Standard" (GB8978-2002). This indicates that the activated sludge process, enhanced through biofortification, effectively treated the natural rubber processing wastewater to meet the required environmental standards. Figure 1 provided in the study illustrates the process of the wastewater treatment project in Jinghong, showcasing the treatment stages and the flow of the wastewater through the system. By utilizing the activated sludge process, coupled with the application of biofortification techniques, Wang *et al.* (2018) successfully achieved efficient treatment of natural rubber processing wastewater, ensuring compliance with wastewater discharge standards.

In summary, the treatment of rubber waste effluent using the activated sludge process has been proven effective in removing organic compounds and other contaminants. The process relies on the metabolic activity of microorganisms to degrade pollutants present in the effluent. Numerous studies have highlighted the high removal efficiencies achieved for pollutants like COD and specific organic compounds, demonstrating the potential of the activated sludge process in treating rubber waste effluent.

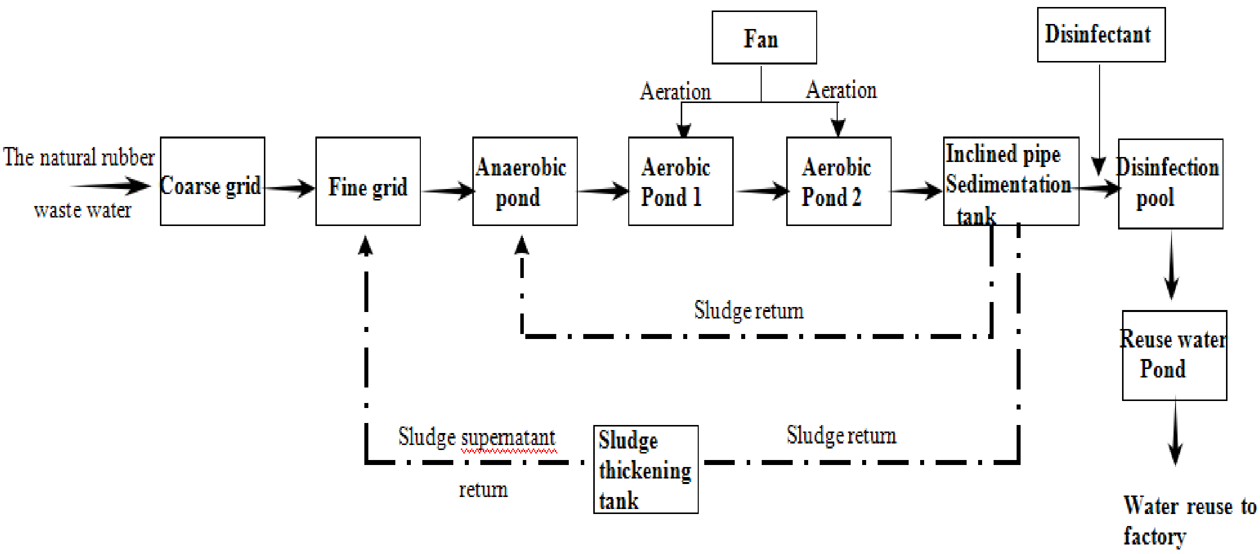

Fig.1 The process of wastewater treatment project in Jinghong (Wang *et al.*, 2018)

Sequential batch reactor (SBR)
This method involves filling a tank with effluent, aerating the tank to promote microbial growth and then settling the solids. This process is repeated in cycles, allowing the

microorganisms to break down the organic matter in the effluent. One method of treating rubber effluent is by using a Sequential Batch Reactor (SBR) (Dutta & Sarkar, 2015). An SBR is a type of activated sludge process that uses a single tank for both the treatment and settling processes. In this process, the wastewater is added to the tank and undergoes a series of treatment cycles, which typically include four stages: fill, react, settle, and decant. During the fill stage, the wastewater is added to the tank until it reaches a predetermined level (Dutta & Sarkar, 2015). Then, during the react stage, microorganisms, such as bacteria and fungi, are added to the tank to break down the organic matter in the wastewater (Shao *et al.,* 2022). This process is known as biological oxidation. After the react stage, the wastewater is allowed to settle, which allows the microorganisms and other solids to settle to the bottom of the tank. The clear effluent is then decanted from the top of the tank and discharged. The use of an SBR for treating rubber effluent has several advantages, including its ability to handle variable loads and high levels of organic matter (Shao *et al.,* 2022). The SBR process is also relatively simple and cost-effective to operate and maintain. However, it is important to note that the effectiveness of an SBR in treating rubber effluent depends on several factors, including the quality of the influent wastewater, the design of the SBR system, and the operating conditions (Dutta & Sarkar, 2015). Therefore, it is crucial to optimize these factors to ensure optimal treatment efficiency and environmental protection.

The treatment of rubber waste effluent using a specific technique, such as the activated sludge process, may have limited existing literature available on its application in this context. However, based on the understanding of the activated sludge process and its effectiveness in treating various types of wastewaters, it is recommended to employ this technique in the treatment of rubber waste effluent. The activated sludge process has been widely utilized in wastewater treatment due to its ability to effectively remove organic compounds and other pollutants. While there might be a lack of literature specifically focusing on the treatment of rubber waste effluent using the activated sludge process, the fundamental principles and success of this technique in treating similar types of industrial wastewater provide a strong basis for its potential application in the rubber waste effluent treatment.

The activated sludge process involves the introduction of wastewater into an aeration tank where microorganisms, primarily bacteria and protozoa, break down organic matter through biodegradation. This process can significantly reduce organic compounds, suspended solids, and other pollutants present in the effluent.

By applying the activated sludge process to rubber waste effluent treatment, it is expected that the organic compounds, such as proteins, carbohydrates, and fats typically found in rubber processing wastewater, can be effectively degraded. Additionally, the process can help reduce other contaminants, such as nitrogenous compounds and toxic components, contributing to the overall improvement in effluent quality. While further research and experimental studies specific to rubber waste effluent treatment using the activated sludge process may be needed to fully understand its application and optimize the process parameters, the existing knowledge and success in treating similar industrial wastewaters support the recommendation of employing this technique for the treatment of rubber waste effluent. Figure 2 illustrates the operational steps involved in the sequencing batch reactor process.

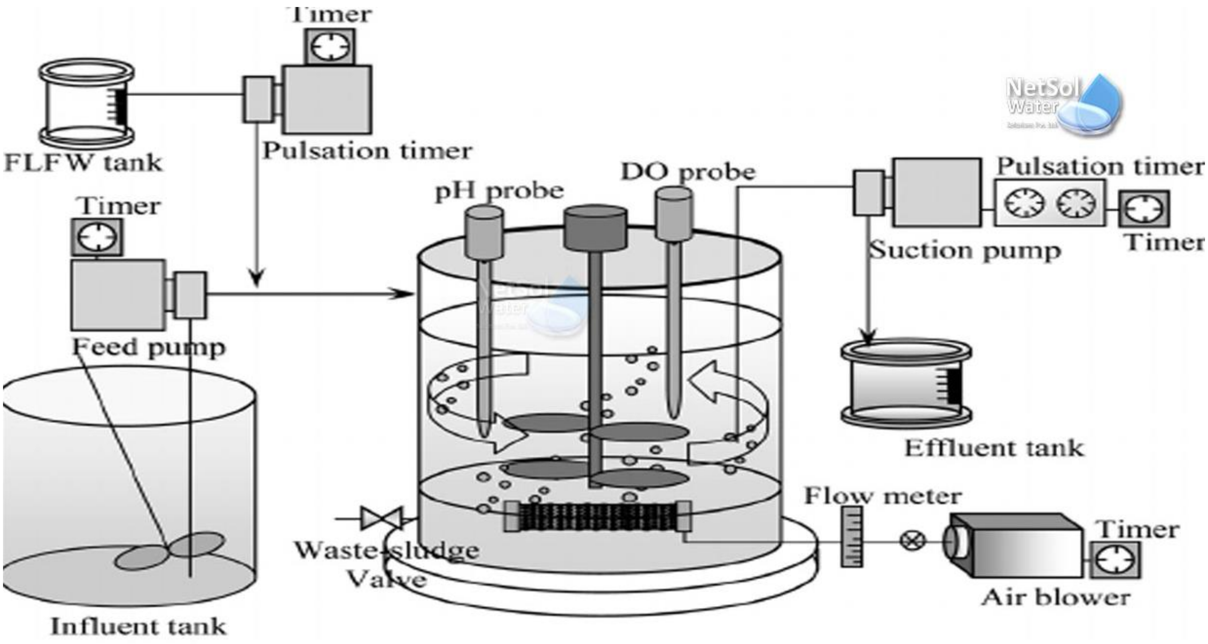

Figure 2: the process of sequencing batch reactor (Shao *et al.*,2022).

In summary, although there might be a lack of literature specifically addressing the treatment of rubber waste effluent using the activated sludge process, the proven success and effectiveness of this technique in treating various types of wastewater make it a recommended approach. Further research and experimentation can help provide more comprehensive insights into the specific

Membrane bioreactor (MBR)
Membrane technology is another method that can be used to treat rubber effluent. Membrane filtration is a process that separates solids, contaminants, and other substances from water by passing it through a semi-permeable membrane (Pervez *et al.,* 2020). The size of the pores in the membrane determines what substances can pass through and what substances are retained.

Membrane bioreactor (MBR) technology has proven to be an effective and reliable method for wastewater treatment across various industries. However, one area that remains largely untapped is the treatment of rubber processing effluent. This writeup explores the significant benefits of MBR treatment and highlights the missed opportunities in utilizing this technology for rubber processing wastewater (Pervez *et al.,* 2020). MBR treatment combines the conventional activated sludge process with a membrane filtration system, offering several advantages over traditional treatment methods. The integration of membranes enhances solid-liquid separation, resulting in higher-quality effluent with reduced suspended solids, pathogens, and other contaminants. Moreover, MBR systems occupy smaller footprints compared to conventional treatment plants, making them ideal for industries with space constraints. The rubber processing industry generates substantial amounts of wastewater laden with various pollutants, including organic compounds, suspended solids, ammonia, and heavy metals (Iorhemen *et al.*, 2016). If left untreated, this effluent can pose significant environmental risks, contaminating water bodies and negatively impacting ecosystems. Therefore, finding efficient treatment solutions for rubber processing effluent is of utmost importance.

Despite the clear advantages of MBR technology, its application in rubber processing effluent treatment has been limited. Several factors contribute to this oversight. Firstly, the complex composition of rubber processing effluent poses challenges for membrane fouling, which can affect system performance. Additionally, the high chemical oxygen demand (COD) and nitrogen content of rubber processing effluent require tailored treatment approaches (Iorhemen *et al.,* 2016). However, recent advancements in membrane technology, such as the development of fouling-resistant membranes and improved cleaning techniques, have addressed many of the challenges faced in treating complex industrial wastewaters. These advancements provide an opportunity to reevaluate the potential of MBR treatment for rubber processing effluent (Rahman *et al.,* 2023). Implementing MBR technology in rubber processing wastewater treatment could yield numerous benefits. It would improve the overall quality of treated effluent, ensuring compliance with stringent environmental regulations (Iorhemen *et al.,* 2016). Additionally, the compact nature of MBR systems allows for decentralized treatment, reducing the need for long-distance transportation of wastewater and associated costs. Furthermore, MBR treatment offers the possibility of resource recovery. By extracting valuable components, such as rubber latex and other organic compounds, from the effluent, the rubber processing industry could create a closed-loop system, minimizing waste and enhancing sustainability (Iorhemen *et al.,* 2016).

In a nut-shell, while membrane bioreactor treatment has proven to be highly effective in various wastewater treatment applications, its potential for rubber processing effluent remains largely untapped. By overcoming the challenges associated with membrane fouling and adapting the technology to meet the specific needs of rubber processing wastewater, MBR systems could revolutionize the treatment of this effluent. Unlocking the benefits of MBR treatment in the rubber industry would not only mitigate environmental concerns but also contribute to the overall sustainability and efficiency of the sector.

Upflow anaerobic sludge blanket (UASB) reactor

The Upflow Anaerobic Sludge Blanket (UASB) reactor is a type of anaerobic digester used to treat various types of wastewaters, including rubber waste effluent. Rubber waste effluent is a type of industrial wastewater that contains high levels of organic compounds, which can be difficult to treat using conventional treatment methods (Lettinga & Hulshoff Pol, 1991). The UASB reactor is an efficient and cost-effective way to treat rubber waste effluent. It operates by creating an anaerobic environment where microorganisms break down organic matter and produce biogas (primarily methane and carbon dioxide) (Sittipong *et al.,* 2018). The reactor contains a sludge blanket that acts as a filter and a source of microorganisms that digest the organic matter. The UASB reactor is capable of removing a wide range of pollutants from rubber waste effluent, including BOD (Biochemical Oxygen Demand), COD (Chemical Oxygen Demand), and suspended solids. It is also effective in reducing the concentration of toxic compounds such as phenols, sulfides, and ammonia (Lettinga & Hulshoff Pol, 1991).

Tanikawa *et al.* (2016) conducted a pilot-scale experiment to treat natural rubber processing wastewater using a combination system comprising a two-stage up-flow anaerobic sludge blanket (UASB) and a downflow hanging sponge (DHS) reactor for over 10 months. The system demonstrated an impressive chemical oxygen demand (COD) removal efficiency of 95.7%±1.3% at an organic loading rate of 0.8 kgCOD/(m3.d). The study found that sulfate-reducing bacteria (SRB), particularly hydrogen-utilizing SRB, exhibited higher activity than methane-producing bacteria (MPB) in the retained sludge from the UASB. Conversely, MPB displayed superior acetate-utilizing activity compared to SRB in the second stage of the reactor. Implementing the two-stage UASB-DHS system resulted in a significant reduction of power consumption by 95% and excess sludge by 98%. Moreover, this system offers the potential to prevent the release of greenhouse gases (GHG), such as methane. An additional benefit of the system was the recovery of methane from the two-stage UASB, which could fulfill the electricity requirements for operating the two-stage UASB-DHS system. This recovered methane accounted for approximately 15% of the electricity consumed in the natural rubber manufacturing process. Figure 3 illustrates the temporal changes in methane-producing and sulfate-reducing activities of the retained sludges from the first and second stages of the UASB reactor, with "N.D." indicating activities that were not detected. Overall, the combination of the two-stage UASB-DHS system showcased remarkable treatment efficiency, reduced energy consumption, minimized excess sludge production, and the potential for utilizing recovered methane for electricity generation, thereby contributing to sustainable wastewater management in natural rubber processing.

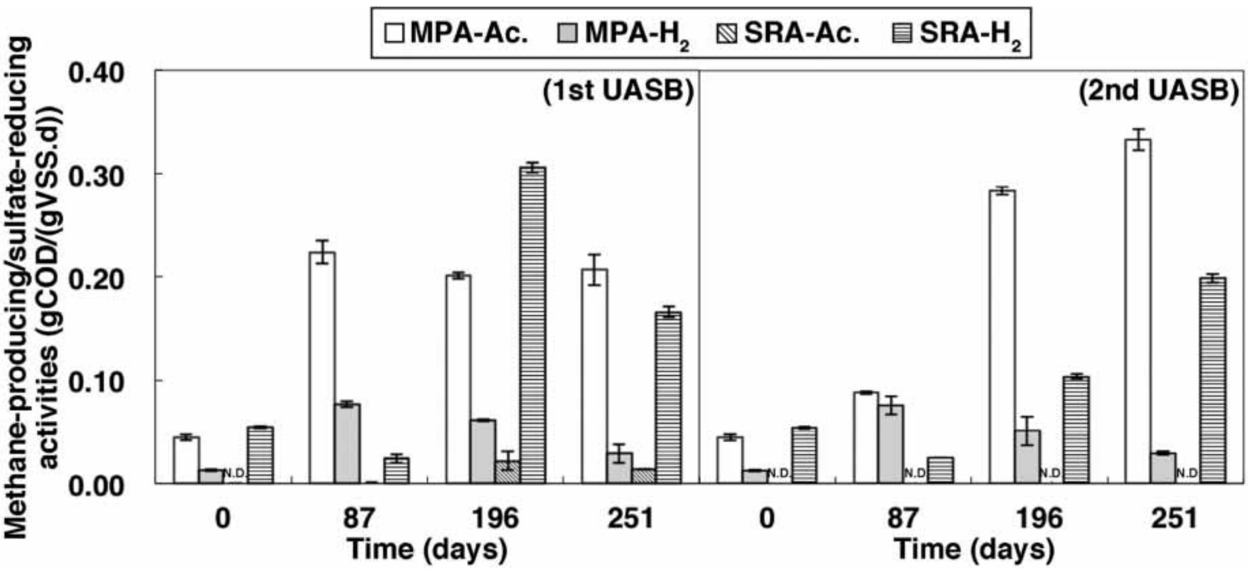

Figure 3: Time course of methane-producing and sulfate-reducing activities of the retained sludges of the first and second stages of the UASB reactor (N.D.: not detected) (Tanikawa *et al.*, 2016).

Trickling filter

Trickling filters are a type of biological wastewater treatment process that use microorganisms to remove pollutants from wastewater. The process involves passing the wastewater through a bed of porous material, such as rocks, gravel, or plastic media, which provides a surface for the microorganisms to grow on (Metcalf *et al.,* 2014). As the wastewater trickles through the bed, the microorganisms remove pollutants through a process of biodegradation.

Rubber waste effluents can be treated using a trickling filter system. The effluents from rubber processing facilities can contain a variety of pollutants, including organic compounds such as phenols, formaldehyde, and other toxic substances. These pollutants can be effectively removed through the use of a trickling filter system (Sittipong *et al.,* 2018).

The first stage of treatment involves the removal of large solids and oils from the effluent using screens, grit chambers, and oil separators. The effluent is then fed into the trickling filter where it trickles through the media bed. The microorganisms that grow on the media feed on the pollutants in the effluent, breaking them down into simpler, less harmful compounds. The treated effluent is then collected and discharged into a receiving water body or reused in the process (Abdullah *et al.,* 2016).

One of the advantages of using a trickling filter system for rubber waste effluent treatment is that it is a relatively simple and low-cost technology compared to other treatment processes

(Abdullah *et al.,* 2016). Additionally, the system can be operated using minimal energy and maintenance requirements. However, the system requires a large land area to accommodate the media bed, which can be a disadvantage in areas where land is scarce (Sittipong *et al.,* 2018).

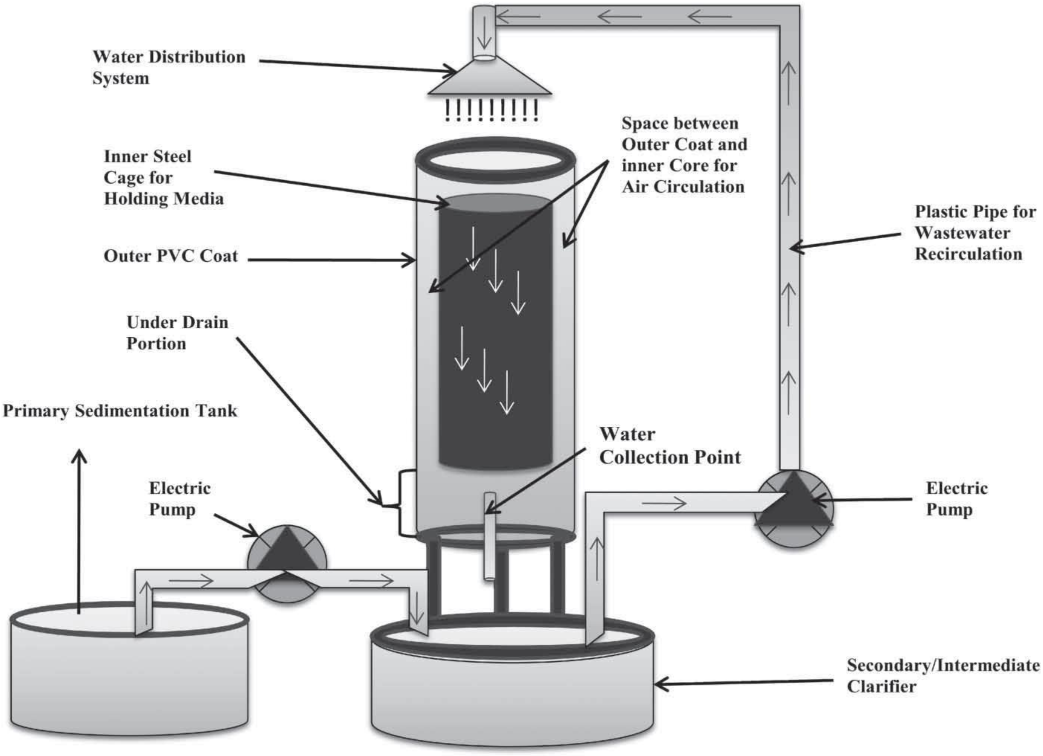

Figure 4. Schematic of laboratory scale biological trickling filter (BTF) set-up for wastewater treatment (Naz *et al.*, 2014)

Naz *et al.* (2014) conducted an assessment of different packing media for biological trickling filters (BTFs) with a focus on wastewater produced from rubber processing. The study aimed to develop a simplified model to describe the capacity of BTFs for biochemical oxygen demand (BOD) removal. Four types of media, including rubber, polystyrene, plastic, and stone, were investigated at temperature ranges of 5–15°C and 25–35°C. The results showed that the average removal of both chemical oxygen demand and BOD exceeded 80% and 90%, respectively, in the temperature ranges of 5–15°C and 25–35°C. The use of different filter media in BTFs resulted in a reduction of faecal coliforms. At the lower temperature range of 5–15°C, the geometric mean of faecal coliforms was reduced by 4.3, 4.0, 5.8, and 5.4 log10 for polystyrene, plastic, rubber, and stone media, respectively. Similarly, at the higher temperature range of 25–35°C, the reduction in faecal coliform count was 3.97, 5.34, 5.36, and 4.37 log10 for polystyrene, plastic, rubber, and stone media, respectively. The study also developed a simplified model to estimate the optimal BOD loading rates (Bvd) for designing robust BTF systems using suitable filter media. The findings suggested that highly efficient BTFs can be designed using various filter media capable of treating organic loading rates of more than 3 kg BOD/m3 day. These BTF systems have the potential to effectively remove BOD and microbial contaminants from wastewater, making them suitable for potential reuse in developing countries. Figure 4 presents the schematic representation of the laboratory-scale set-up for biological trickling filter (BTF) used in the study for wastewater treatment. In general, the assessment of different packing media for BTFs demonstrated their efficacy in wastewater treatment, including rubber processing effluent. The study's findings contribute to the design and implementation of efficient BTF systems for organic and microbial contaminant removal, enabling potential wastewater reuse in developing countries.

The Future Outlook for The Application of Microbial Techniques in The Treatment of Rubber Waste Effluent

The use of microbial approaches for treating rubber waste effluent is a promising field with significant potential for the future ((Iorhemen *et al*., 2016). One approach is bioremediation, where microorganisms are used to break down the organic compounds in the rubber waste effluent. This process can be enhanced by adding specific microorganisms that are known to be effective in breaking down rubber waste compounds (Sittipong *et al*., 2018).

Another approach is the use of microbial fuel cells, which use microorganisms to generate electricity while simultaneously treating the rubber waste effluent. This approach has the potential to generate renewable energy while reducing the environmental impact of rubber waste. In addition to these approaches, research is also being conducted on the use of microorganisms to produce valuable products from rubber waste, such as biofuels, bioplastics, and other useful chemicals (Abdullah *et al.,* 2016; Sittipong *et al*., 2018; Naz *et al.,* 2014).

Overall, the future prospect of using microbial approaches for treating rubber waste effluent is bright. Continued research and development in this field have the potential to lead to more effective, efficient, and sustainable methods for managing rubber waste, while also generating useful products and reducing the environmental impact of this industry.

Challenges of the Application of Microbial Techniques in The Treatment of Rubber Waste Effluent

The application of microbial techniques in the treatment of rubber waste effluent can face several challenges, including (Al-Musawi *et al.,* 2019; Koul *et al.,* 2022; Zheng *et al.,* 2013; Wang *et al.* 2018):

i. High toxicity: Rubber waste effluent can contain toxic substances, such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), and phenols, which can be harmful to microorganisms and inhibit their growth and activity.
ii. Low biodegradability: Rubber waste effluent can also contain complex organic compounds that are difficult for microorganisms to break down, leading to slow degradation rates and long treatment times.
iii. High variability: The composition of rubber waste effluent can vary significantly depending on the type of rubber processed and the manufacturing process used. This variability can make it difficult to develop effective microbial treatment strategies.
iv. Nutrient limitations: Microorganisms require specific nutrients, such as nitrogen and phosphorus, to grow and carry out biodegradation. Rubber waste effluent may be deficient in these nutrients, requiring the addition of external nutrient sources.
v. Process optimization: Microbial treatment systems require careful process optimization to ensure that conditions such as pH, temperature, and dissolved oxygen levels are suitable for microbial growth and activity. Maintaining optimal conditions can be challenging, especially in large-scale treatment systems.
vi. Cost-effectiveness: Developing and implementing microbial treatment systems can be expensive, and the cost-effectiveness of these systems depends on the specific conditions of the effluent and the treatment goals.

In summary, the application of microbial techniques in the treatment of rubber waste effluent requires careful consideration of the challenges involved and the development of effective strategies to overcome them.

Conclusion

Progress has been made in the mitigation of rubber waste effluent employing microbial methodologies. Microbial techniques, such as bioremediation, have shown promise in treating wastewater from rubber processing facilities. Trickling filter systems and microbial fuel cells have been found to be effective in removing various pollutants, including phenols and formaldehyde. These methods are sustainable, environmentally friendly, and low-cost options for the treatment of rubber waste effluent. Further research is needed to optimize and scale up these techniques to make them more practical for industrial applications. Nonetheless, microbial techniques hold great potential as an alternative to traditional treatment methods and can contribute to the sustainable management of rubber waste effluent.

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