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Imperative assessment on the current status of rubber wastewater treatment: Research development and future perspectives

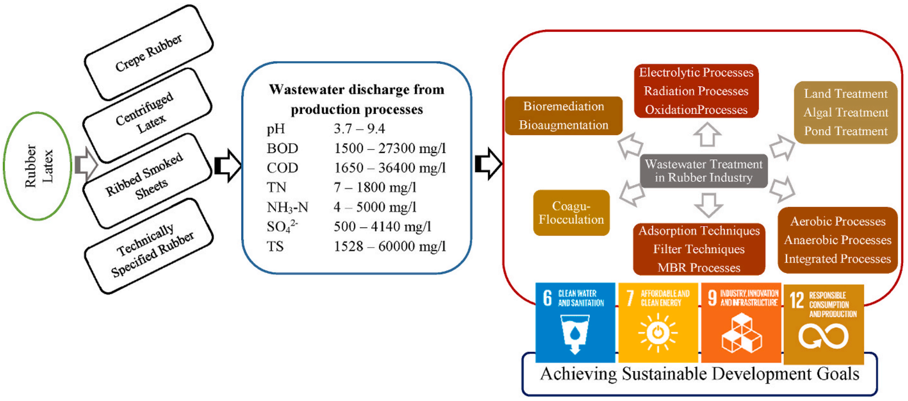
W.S.M.S.K. Wijerathna [a], T.I.P. Wimalaweera [b,c,d], D.R. Samarajeewa [a,*], L.M.L.K.B. Lindamulla [a,e], R.M.L.D. Rathnayake [a], K.G.N. Nanayakkara [a], V. Jegatheesan [e], Yuansong Wei [b,c,d,f], K.B.S.N. Jinadasa [a,c]

[a] Department of Civil Engineering, Faculty of Engineering, University of Peradeniya, Peradeniya, 20400, Sri Lanka
[b] State Key Joint Laboratory of Environmental Simulation and Pollution Control, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, 100085, China
[c] Laboratory of Water Pollution Control Technology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, 100085, China
[d] University of Chinese Academy of Sciences, Beijing, 100049, China
[e] School of Engineering, RMIT University, GPO Box 2476, Melbourne, 3001, Australia
[f] National Institute of Fundamental Studies, Hantana Road, Kandy, 20000, Sri Lanka

HIGHLIGHTS

- Forecasted global industrial rubber market expansion is at CAGR of 5.2% by 2026.
- Rubber industry uses high volumes of water in production (e.g. 20–50 L/1 kg of Crepe rubber, 50–60 L/1 kg of block rubber).
- On average 20 tonnage manufacturing process generates 410 m^3 of toxic effluent per day in a rubber factory.
- Conventional techniques are inadequate to treat wastewater up to discharge standards.
- Conventional to advanced treatment techniques used are reviewed in this paper.

GRAPHICAL ABSTRACT



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ABSTRACT

The environment has been significantly impacted by the rubber industry through the release of large quantities of wastewater during various industrial processes. Therefore, it is crucial to treat the wastewater from the rubber industry before discharging it into natural water bodies. With the understanding that alarmingly depleting freshwater sources need to be preserved for future generations, this paper reviews the status of the rubber industry and the pollution caused by them, focusing mainly on water pollution. The review pays special attention to the recent advancements in wastewater treatment techniques for rubber industry wastewater categorizing

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* Corresponding author.
E-mail addresses: wsmsamanthi94@eng.pdn.ac.lk (W.S.M.S.K. Wijerathna), ishankapra@mails.ucas.ac.cn (T.I.P. Wimalaweera), dinushi.s@eng.pdn.ac.lk (D.R. Samarajeewa), lahikos@gmail.com (L.M.L.K.B. Lindamulla), lashithar@eng.pdn.ac.lk (R.M.L.D. Rathnayake), nadeen@eng.pdn.ac.lk (K.G.N. Nanayakkara), jega.jegatheesan@rmit.edu.au (V. Jegatheesan), yswei@rcees.ac.cn (Y. Wei), shamj@eng.pdn.ac.lk (K.B.S.N. Jinadasa).

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Pollution
Treatment
Sustainable use

them into pre-treatment, secondary, and tertiary treatment processes while discussing the advantages and disadvantages. Through a comprehensive analysis of existing literature, it was determined that organic content and NH_4^+ are the most frequently focused water quality parameters, and despite some treatment methods demonstrating superior performance, many of the methods still face limitations and require further research to improve systems to handle high organic loading on the treatment systems and to implement them in industrial scale. The paper also explores the potential of utilizing untreated or treated wastewater and byproducts of wastewater treatment in contributing towards achieving several United Nations sustainable development goals (UN-SDGs); SDG 6, SDG 7, SDG 9, and SDG 12.

1. Introduction

The history of natural rubber (NR) dates back to Christopher Columbus' discovery of natives playing with balls made of rubber in Haiti in 1493. Since then, the rubber industry has evolved through many innovative methods and has become a major industry that earns foreign exchange for the economies of many countries.

The rubber tree (*Hevea brasiliensis*), is a major export crop in many Asian countries, including Malaysia, Thailand, Vietnam, Indonesia, India, China, and Sri Lanka (Mohammadi et al., 2010; Nguyen and Luong, 2012; Rudra Paul et al., 2022). NR is produced by pure poly-cis-1,4-isoprene that is extracted from rubber trees and synthetic rubber is most of the time produced using petroleum and other fossil fuels. The rubber processing industry uses a large volume of fresh water in its production. As per details by Gamaralalage et al. (2016) and Nguyen and Luong (2012), the production of centrifuged latex, crepe rubber, technically specified rubber (TSR), and ribbed smoked sheets (RSS) use nearly 3.7–18 L/kg, 20–50 L/kg, 15 L/kg and 10–25 L/kg of fresh water in their production processes, respectively. Mohammadi et al. (2010) have reported that on average 20.5 L of effluent is produced when producing 1 kg of rubber by a single rubber factory in a day, leading the industry to become the most water-polluting industry in several countries. Centrifugation, coagulation, wet-milling, dipping and cutting, lamination, washing, and drying are some steps in the rubber production processes, where large amounts of wastewater are released with high levels of pollutants such as chemical oxygen demand (COD), suspended solids (SS), biochemical oxygen demand (BOD) and nitrogen-containing pollutants (Tanikawa et al., 2020b; Watari et al., 2016).

The improper discharge of highly polluted rubber wastewater without proper treatment has resulted in negative effects on the environment such as oxygen depletion, interference with aquatic life, fish kill (Atagana et al., 1999), eutrophication (Abraham et al., 2017; Arimoro, 2009; Pillai and Girish, 2014; Tanikawa et al., 2016b), malodour problems (Mohammadi et al., 2010), allergies (Hatamoto et al., 2012) and health hazards. These issues impact both human beings and aquatic life in the both short and long term (Dey et al., 2020; Ismail and Suja, 2019; Krainara et al., 2020). Additionally, water scarcity has become a significant concern for the industry, leading to a focus on sustainable production by minimizing water usage and reusing generated wastewater. To address these problems, conventional and advanced treatment approaches are being used to treat wastewater from rubber product manufacturing processes.

In general, there are several commonly used treatment techniques when treating industrial wastewater such as physical (adsorption, ion exchange, membrane filtration), chemical (coagulation-flocculation, photolysis, electrochemical), biological (enzyme-assisted, bacteria-assisted, fungal-assisted), advanced oxidation processes (photo-Fenton, ozonation, photocatalytic, sono catalytic) and hybrid methods (Chan et al., 2009; Jegatheesan et al., 2016; Lin et al., 2012; Neoh et al., 2016; Roccaro, 2018; Solayman et al., 2023). These techniques generally offer straightforward, adaptable, effective, and environmentally friendly benefits depending on the approach taken. However, certain drawbacks in the aspects of cost implications, challenges related to secondary sludge disposal, pH sensitivity, and treatment duration are inevitable (Solayman et al., 2023).

Among the described various techniques, several methods are also being employed for treating wastewater in the rubber processing industry. These techniques can be classified into several categories, such as coagulation-flocculation-based processes, filtration and separation processes, degradation processes (including conventional biological treatment processes such as pond systems, and aerobic-anaerobic reactors), and oxidation processes (Ho et al., 2023; Mokhtar et al., 2015; Sulaiman et al., 2010). However, recent attention has been directed toward advanced wastewater treatment techniques such as bioremediation, adsorption, membrane bioreactors, and oxidation/radiation processes. This review paper aims to assess the current state of the rubber industry, its environmental impacts, and the available wastewater treatment techniques, ranging from conventional to advanced, with a focus on sustainable waste reuse. The paper also emphasizes the importance of linking parallel research work to achieve the UN-SDG targets related to clean water and sanitation (SGD 6), affordable and clean energy (SDG 7), industry, innovation, and infrastructure (SDG 9), and responsible consumption and production (SDG 12) (United Nations, 2015).

2. Rubber industry

2.1. Current situation of the rubber industry

The global economy is significantly impacted by the rubber industry, with an increase in both the consumption and production of rubber over the past few decades (Supplementary Data – Fig. S1). Southeast Asian countries are the primary contributors to NR production, accounting for over 75% of the world's rubber production (Supplementary Data – Fig. S2) with Thailand alone producing around 35% of the NR latex required to meet global demand (Jawjit et al., 2010). According to statistics, the total global NR production in 2019 was 13,764 thousand tonnes, while the demand was 13,702 thousand tonnes. Although large cooperatives operate at capacities of about 500–1000 tonnes per year in most countries, smallholder sectors are the dominating rubber producers. In Malaysia, Thailand, India, and Indonesia, the smallholders account for 93%, 90%, 89%, and 85% of national rubber production, respectively (Fox and Castella, 2013).

2.2. Environmental pollution by the rubber industry and related health issues

The rubber industry is one of the industries that contribute majorly to water pollution. It uses colossal volumes of water for daily production processes which contribute significantly to water stream pollution by releasing high-strength wastewater. Volumes of wastewater can go even up to 1000 m^3 per day when considering larger cooperatives (Idris et al., 2013). Several chemicals are used in the manufacturing process of various rubber products at different stages of processing which are illustrated in Supplementary Data – Fig. S3. Hence, these wastewaters contain small amounts of latex and serum, immense amounts of proteins, sugar, lipids, carbohydrates, carotenoids, and organic and inorganic salts (Wang et al., 2013a). Though the wastewater characteristics may vary from country to country, it is reported that wastewater released from rubber product processing plants, especially from centrifuged latex processing plants, release high-strength acidic wastewater. In addition, the chemicals added during the production process add high concentrations of phosphorous and heavy metals such as Zn and Cu for the effluent discharge (Jawjit and Liengcharernsit, 2013; Sulaiman et al., 2010).

2.3. *Characterization of rubber wastewater and worldwide regulatory standards*

To reduce water pollution, many countries have established specific discharge standards for rubber wastewater. Table 1 presents country-specific discharge standards and Table 2 presents characteristics of raw wastewater released from different types of rubber factories. The data in these tables reveal that the COD values often exceed the discharge limits, and the COD: BOD ratio in centrifuged latex effluent ranges from 1.1 to 2.76 which comes under the category of "not easily biodegradable". However, most regulatory agencies in these countries do not enforce discharge limits for NO_3–N, NO_2–N, PO_4–P, and benzene compounds in rubber wastewater. Despite this, the use of chemicals during manufacturing may result in the release of high concentrations of these toxic compounds into surface waters once discharged-untreated and they can cause serious adverse health impacts on individuals who consume such water.

3. Rubber wastewater treatment techniques

Due to the high ammonization of natural latex for stabilizing purposes and coagulation with highly concentrated acidic chemicals used in the production process, wastewater generated during latex production is considered the most polluted type (Madhu et al., 1994). Much research has been conducted to investigate the effectiveness as well as the issues related to the conventional treatment techniques used in rubber wastewater. A summary of some typical industry-applied rubber wastewater treatment techniques is depicted in Fig. 1 (Gamaralalage et al., 2016), and conventional to researched treatment methods are discussed below. In some cases, as some of these rubber processing and wastewater treatment plants are located in industrial zones, effluent from each of the factories will be taken to a centralized treatment system, treated adequately, and will be released into the environment.

3.1. *Pre-treatment as the primary treatment*

Often pre-treatment is focused on the removal of SS which could adversely affect the biodegradation of organic matter in subsequent treatment processes and therefore, the most common approach used is coagulation-flocculation treatment. Commercial alum, poly aluminium chloride, ferric chloride, lime, polyacrylamide (PAM) partially hydrolysed with soda, and $Al_2(SO_4)_3$ are some coagulants used in the coagulation-flocculation process (Rudra Paul et al., 2022). These coagulants have proven efficient in contaminant removal when combined with various other processes which are summarized in Table 3. Though there are many advantages of the commercially available coagulants, potential disadvantages include the generation of high volumes of hazardous sludge, high procurement costs, detrimental effects on environmental and human health, and costly options for the disposal of generated sludge (Idris et al., 2013; Massoudinejad et al., 2015; Ngteni et al., 2020). Although, a typical coagulation process can remove more than 99% COD from rubber wastewater (Ngteni et al., 2020) when considering very high COD concentrations, either a high dosage of coagulants is required which would ultimately result in high operational costs. Nonetheless, modifications/low-cost alternatives to the coagulant (Idris et al., 2013) or modified coagulation-flocculation process can eliminate these cost concerns.

A more advanced stage of coagulation, which is electrocoagulation where the wastewater is treated without a coagulant has several advantages over the conventional technique such as the use of simple equipment, easy operations, inexpensive cost-effective process, and a reduced reaction time (Rusdianasari et al., 2021). The Fenton oxidation process is based on highly reactive hydroxyl radical generation which is effective in degrading organic chemicals and the electrocoagulation process which is based on redox reactions seems more suitable as pre-treatments for high-strength latex production and processing wastewater which can reduce COD levels of 14,000–17,000 mg/L by more than 80% (Devi et al., 2018; Thangarani and Kanmani, 2007). This method has further advantages such as high efficiency in removing organic compounds, low operating costs, low toxicity of the reagents, high efficiency, simplicity, low amount of residues, and high potential to treat many different compounds (Pendashteh et al., 2017). However, Fenton oxidation combined with the biological process may not be the best option to treat NH_3 content to achieve regulatory standards due to

Table 1
Discharge standards for the rubber industry wastewater.

Parameter	Sri Lanka		Malaysia	Nigeria	China	Vietnam (QCVN 01:2008/BTNMT – Category A)	Myanmar
	Latex concentrate industries	Standard Sri Lanka Rubber, Crepe Rubber, RSS					
Reference	(Board of Investment-Sri Lanka, 2011)		Mohammadi et al. (2010)	Owamah et al. (2014)	Wang et al. (2013a)	Nguyen and Luong (2012)	("National Environmental Quality (Emission) Guidelines - Myanmar,")
pH	6.5–8.5	6.5–8.5	–	6–9	6–9	6–9	6–9
Total Suspended Solids	100	100	–	30	70	100	50
Total Solids	1500	1000	1000	–	–	–	–
Total Dissolved Solids (TDS)	–	–	–	2000	–	–	–
Biochemical Oxygen Demand (BOD)	60	50	100	50	30	50	–
Chemical Oxygen Demand (COD)	400	400	400	–	100	250	250
Total Nitrogen (TN)	300	60	300	–	–	60	15
Ammoniacal Nitrogen (as N)	300	40	300	–	20	40	–
Sulfides (as S^{2-})	2.0	2.0	–	–	–	–	1
Nitrates	–	–	–	20	–	–	–
Total Phosphate	–	–	–	5	–	–	5

(All parameters are in mg/L except for pH).

Table 2

Raw wastewater characteristics of different types of rubber industries.

Reference	Mohammadi et al. (2010)	Mokhtar et al. (2015)	Xin et al. (2013)	Lopes et al. (2013)	Gamaralalage et al. (2016)	Nguyen and Luong (2012)	Ashok et al. (2015)	Abraham et al. (2017)	Asia and Akporhonor (2007)	Rubber Research Institute of Sri Lanka (2003)	Jawjit and Liengcharernsit (2013)
Country	**Worldwide data**	**Malaysia**	**Spain**	**Spain**	**Sri Lanka**	**Vietnam**	**India**	**India**	**Nigeria**	**Sri Lanka**	**Thailand**
Wastewater type	Average rubber	NR latex	Rubber parts demoulding	Rubber tubing extrusion	Centrifuged latex	latex	NR latex	NR latex	Average	NR latex	Concentrated latex
pH	3.7–5.5	3.9	6.4	5.35	6	8.09–9.42	4.6	3.6	8.1	3.7	3.9–4.4
COD	3500–14,000	1650	14,829	26,700	4500	11,935–26,914	30,000	36,400	3142	6201	3890–4860
BOD	1500–7000	1500	–	–	–	7590–13,820	10,867	27,300	2610	3192	2400–2860
Alkalinity	–	–	–	–	–	–	–	–	424	–	–
DO	–	–	–	–	–	–	–	–	4.7	–	–
TN	200–1800	–	–	–	–	450–1306	–	–	7.85	616	–
TKN	–	–	–	–	–	–	–	7000	–	–	836–1397
NH_3–N	–	–	–	–	–	285–1043	–	5000	4.49	401	316–578
Total Solids	–	–	–	–	–	–	–	60,000	1528.5	7576	–
Suspended Solids	200–700	–	54	–	–	468–2220	2132	–	1078.5	190	265–856
Dissolved Solids	–	18,710	–	–	–	–	–	58,000	–	–	7780–8650
VSS	–	–	49	–	–	–	–	–	–	–	154–292
Turbidity (NTU)	–	332	44	44	–	–	–	350	702 FTU	–	–
Colour (Pt/Co)	–	1306	–	–	–	–	–	–	2430	–	–
Phosphate	–	–	–	–	–	–	–	2600	1.32	–	–
TP	–	–	–	–	173	–	–	–	–	–	86.46–126
Sulphate	500–2000	3339	–	–	–	–	–	–	–	1610	1247–4140
Pb	–	–	–	–	–	–	–	–	0.211	–	–
TOC	–	6765	4420	6293	2500	–	–	–	–	–	–
Conductivity (uS/cm)	–	31,700	766	350	8000	–	–	–	320 S/cm	–	–
O&G	–	–	15.1	–	–	–	–	–	–	–	–

(All parameters are in mg/L except for pH and where specified).

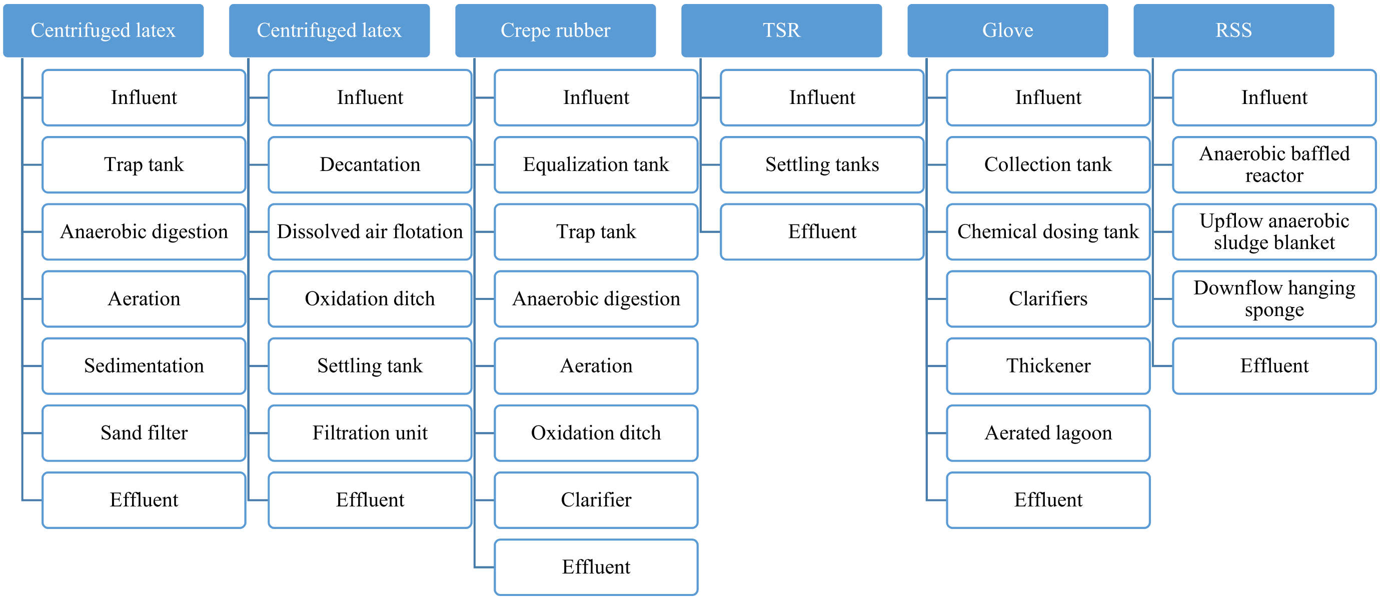

Fig. 1. Rubber wastewater treatment methods.

comparatively low levels of removal.

Some of these processes have reported comparatively low-cost methods to be used as pre-treatment steps in rubber wastewater treatment processes. For instance, the electro-Fenton process followed by coagulation has reported an operational cost of $ 7–8.5 per kg of COD reduction in latex production and processing wastewater treatment (Devi et al., 2018) and in addition, zinc removal using chemical precipitation-flocculation process using polyelectrolyte (LT 27) and precipitant Na_2S has surprisingly reported costing $ 0.26/m^3 of wastewater treated (Subbiah et al., 2000).

While it is possible to effectively eliminate solids from various treatment processes, achieving adequate organic matter removal for high organic loadings is often not reported in many pre-treatment methods. Among these methods, the Fenton oxidation process appears to be a viable and effective approach for treating rubber wastewater with high organic loading rates. However, although some methods achieve removal efficiencies of over 80%, they still fall short of meeting the required discharge standards for COD removal. Hence, additional treatment steps are required to achieve regulatory discharge standards after utilizing these pre-treatment methods.

3.2. Secondary treatment techniques

During the primary treatment, most of the suspended and colloidal particles are expected to be removed. However, as mentioned in the previous section, it does not contribute much towards the removal of organics or nutrients in rubber wastewater. Hence, secondary treatment techniques are used for this purpose, and as dissolved organic matter (DOM) of rubber factory effluent is considered the major pollutant among other contaminants, and since it is highly biodegradable, in most cases this DOM content can be treated using biological wastewater treatment methods. Aerobic, anaerobic, facultative ponds, anaerobic filter beds, rotating bio discs, aerated lagoons, UASBs, and oxidation ditch systems are some of the conventional treatments used in the field according to the facilities and the land availability (Mohammadi et al., 2010; Nguyen and Luong, 2012). Tables 4–6 summarize some upgrades proposed by the researchers for the conventional treatment techniques to overcome the limitations faced by the conventional techniques.

3.2.1. Biological treatment techniques using land treatment, algae, and ponds

Major mechanisms of nitrogen removal in pond systems and land treatment systems are assimilation, ammonia volatilization, and nitrification-denitrification processes which occur in the treatment system (Bich et al., 1999; John, 1985). Table 4 summarizes the research on land/pond treatment in the treatment of rubber wastewater. Covered Activated Ditch (CAD) type reactors with bio-brush media are observed to overcome limitations in pond systems and a high-rate treatment system that could be set up at a low cost. Further, swim-bed technology which is another similar concept studied in wastewater treatment involves an acryl-fibre biomass carrier and a biofringe, and the method has proven 96% removal efficiency of the organic matter though the nitrogenous compound removal was not very well addressed (Le et al., 2012). In overview, it can be observed that the methods based on Waste Stabilization Ponds (WSPs) can efficiently remove COD levels less than 2500 mg/L however, when it comes to high-strength organic matter they cannot reach up to the specified standards when used as the sole method in the treatment train. Despite having advantages over cost concerns and simplicity in operation, land treatment techniques have major drawbacks with regard to the required land area. This makes it unsuitable for factories that do not have such extent of land available when they are located near urban and overdeveloped areas (John, 1985; Kudaligama et al., 2010).

3.2.2. Bioremediation and bioaugmentation

Bioremediation using the metabolic potential of microorganisms is one of the techniques used in rubber wastewater remediation. Several types of bacteria which are readily available in the rubber processing waste are favourable towards degrading the contaminants. Support from wastewater for the growth of bacteria, the easiness of culture, and rapid growth have made the treatment using bacterial consortium an effective approach as a biological treatment technique. According to Atagana et al. (1999) and Pillai and Girish (2014), *Arthrobacter* sp., *Bacillus* sp., *Lactobacillus* sp., *Pseudomonas* sp., and *Streptococcus* sp. are suitable to remove organic compounds from natural rubber processing wastewater. In addition, *Desulfovibrio* sp., *Desulfitibacter* sp., *Dethiosulfatibacter* sp., and *Clostridium* sp. are sulphate-reducing bacteria that are capable of reducing sulphate levels up to around 87% from rubber sheet wastewater (Promnuan et al., 2019). Removal of nutrients such as nitrates and phosphates was studied by Dey et al. (2020) to find that biofilm forming

Table 3
Pre-treatment options for rubber-processed effluent.

Treatment Method	Wastewater Type	Removal Efficiency (%)							Reference
		COD	SS	Turbidity	NH_3	BOD	Colour	Zinc	
Electrocoagulation process using aluminium-stainless steel electrodes	Rubber liquid waste	56% [114 mg/L]	77.6% [48.2 mg/L]	–	73.5% [2.00 mg/L]	90% [39.7 mg/L]	–	–	Rusdianasari et al. (2021)
Double chamber microbial fuel cell reactor with anode and cathode chambers separated by a Nafion proton exchange membrane	Pretreated latex processing wastewater	96% % [2660 mg/L]	–	–	–	93.3% [953 mg/L]	–	–	Selvaraj et al. (2020)
		88.5% [780 mg/L]	–	–	–	77.6% [280 mg/L]	–	–	
Coagulation using $FeSO_4{\cdot}7H_2O$	Secondary rubber processing effluent	99% [930 mg/L]	98% [1148 mg/L]	–	95% [440 mg/L]	97% [220 ± 4 mg/L]	–	–	Ngteni et al. (2020)
Electro-Fenton process followed by coagulation	Pretreated latex processing wastewater	82% [14,200 mg/L]	–	–	–	51.5% [1965 mg/L]	92%	–	Devi et al. (2018)
		85% [5100 mg/L]	–	–	–	64.3% [785 mg/L]	91%	–	
Coagulation-flocculation (using Alum) process coupled with Fenton oxidation process	$Ca(NO_3)_2$ pre-treated NR latex wastewater	90.3% [688 mg/L]	–	–	–	–	–	–	Pendashteh et al. (2017)
Coagulation-flocculation (using $Al_2(SO_4)_3$) process combined with ozonation process	Discharge unit of the tire manufacturing factory	90.6% [5613 mg/L]	–	–	–	–	–	–	Massoudinejad et al. (2015)
Coagulation and flocculation (using PAC + PAM) combined with the process of hydrolysis acidification – biological contact oxidation – membrane bioreactor	A mix of butyl rubber production wastewater generated from rubber synthesis (alkaline wastewater + cleaning and flushing wastewater)	88.6 ± 6.3%	–	–	–	–	–	–	Zhang et al. (2013)
Coagulation Ferric Sulphate	Concentrated Latex	98% [7857 mg/L]	90% [1208 mg/L]	98% [7243 NTU]	–	–	–	–	Idris et al. (2013)
Dragon fruit foliage plant-based coagulant		94.7% [7857 mg/L]	88.9% [1208 mg/L]	99.7% [7243 NTU]	–	–	–	–	
Ultrasonic irradiation	Rubber mill effluent	91% [6775 mg/L]	76% [1494 mg/L]	–	–	–	–	–	Ye et al. (2010)
Physico-chemical treatment using $–CH_2CH–COONa^+$ succeeded by sand-bed filtration and a column packed with powdered activated carbon	Discharge unit of the rubber processing sewage system	97% [3142 mg/L]	99% [1078.5 mg/L]	–	–	98% [2610 mg/L]	–	–	Asia and Akporhonor (2007)
Pretreatment using photo Fenton oxidation process combined with biological process (SBR)	Centrifuged latex process wastewater	94% [17,188 mg/L]	84% [315]	–	56% [692 mg/L]	92% [3610 mg/L]	–	–	Thangarani and Kanmani (2007)
Chemical precipitation-flocculation process using polyelectrolyte (LT 27) and precipitant Na_2S	Rubber thread manufacturing process wastewater	–	–	–	–	–	–	99% [250–310 mg/L]	Subbiah et al. (2000)
Coagulation process with Na_2S		–	–	–	–	–	–	94% [266 mg/L]	Kida et al. (1997)

(Initial parameter values are presented in [] brackets).

bacterial isolates such as *Cellulosimicrobium* sp., *Aeromonas veronii, Lysinibacillus sphaericus, and Rhodococcus rhodochrous* were able to remove 95% and 75% of nitrate and phosphate respectively from latex wastewater at optimum conditions of pH = 7 and 37 °C.

Bioaugmentation, the process of addition of microorganisms to bioprocesses or bioreactors to improve the degradation capability of microorganisms with regard to specific contaminants has been studied in the treatment of high-strength rubber wastewater. Bioaugmentation treatment processes combined with Anaerobic-Anoxic-Aerobic (A^2O), MEM flora, and A/O biofilm processes are some researched methods for rubber wastewater treatment. Further, bioaugmentation using purple nonsulphur bacteria, an anaerobic process combined with a two-stage bio-contact oxidation cell is studied to enhance the treatment efficiency of various rubber processing wastewater treatment techniques (Jing et al., 2018; Kornochalert et al., 2014). Krainara et al. (2020) studied the behaviour of *Pseudomonas* sp. *and Stenotrophomonas* sp. in removing toxic 2-mercaptabenzothiazole (2-MBT) from latex wastewater to find that a considerable amount of 65–79% of 112 mg/L 2-MBT and 90–93% of 4000 mg/L COD were removed by the consortium.

Studies on bioremediation and bioaugmentation serve as important

Table 4
Secondary treatment of rubber wastewater using land treatment/pond techniques.

Treatment Method	Wastewater Type	Removal Efficiency (%)							Reference
		COD	SS	Turbidity	NH_3–N	BOD	Colour	Other	
Attached-growth waste stabilization ponds	Concentrated latex wastewater after anaerobic pond treatment	81% [1990 mg/L]	–	–	96.6% [474 mg/L]	96% [1418 mg/L]	–	TKN – 92.5% [507 mg/L] Org-N – 33.3% [33 mg/L]	Rakkoed et al. (1999)
Waste stabilization ponds (Latex wastewater mixed with sewage waste)	Centrifuged latex wastewater	90% [8905 mg/L]	–	–	–	93% [3845 mg/L]	–	–	Madhu et al. (1994)
Use of water lettuce macrophyte pond	Rubber processing wastewater	85.5% [74.5 mg/L]	–	–	–	90.6% [206 mg/L]	–	NO_3^- – 88.2% [1 mg/L] PO_4^{3-} – 98.3% [60 mg/L]	Owamah et al. (2014)
Integrated high-rate algal pond (HRAP) system containing water hyacinth (*Eichhornia crassipes*) combined with green alga (*Chlorella vulgaris*)	Diluted skim serum wastewater	98.03% [503 mg/L]	52.63% [37.8 mg/L]	–	–	–	–	TKN – 99.49% [51.1 mg/L]	Bich et al. (1999)
Lagoon system using water hyacinth (*Eichhornia crassipes*)	NR latex wastewater	88.7% [2480 mg/L]	88.9% [810 mg/L]	–	70% [100 mg/L]	94.4% [1430 mg/L]	–	TN – 66.7% [150 mg/L]	John (1985)
Covered activated ditch (CAD) reactors with Bio-brush media	Crepe rubber factory effluent	88.63% [2700 mg/L]	–	–	–	–	–	–	Kudaligama et al. (2010)
Swim-bed technology using acryl-fibre biomass carrier	Latex processing wastewater	96% [1556 mg/L]	–	–	–	–	–	–	Le et al. (2012)

(Initial parameter values are presented in [] brackets).

findings because when bacterial consortiums are used, the extracellular polymeric substances from bacteria act as a protective microenvironment that is resistant to varying pH, osmotic shocks, presence of toxic compounds, desiccation, and other unfavourable conditions that occur in the treatment systems thereby favouring the growth of the microorganisms to increase the rate of bioavailability and degradation of pollutants in the wastewater. In addition, some of these bacterial consortia can be obtained easily from either soil, wastewater, and wastewater sludge. However, on the other hand, it also presents some challenges in giving the ideal growth conditions for the bacteria for cultivating to use in wastewater treatment.

3.2.3. Integrated aerobic and anaerobic processes

As per Table 5, there are many integrated and non-integrated aerobic, anaerobic systems and downflow hanging sponges (DHS) which are used for the treatment of different types of rubber wastewater due to their advantages (Tanikawa et al., 2019b, 2020b; Thongnueakhaeng and Onthong, 2012). DHS reactor can be operated with or without minimal aeration requirements with sponge media acting as a support for biomass in the filter system for nitrifying (*Nitrosomonas* spp., *Nitrospira* spp., *Candidatus Brocadia*), denitrifying (*Comamonas* spp.) and anammox bacteria which are involved in nitrogen removal (Watari et al., 2017a). The post-DHS reactor with anoxic conditions for nitrogen removal where sodium acetate is introduced as the carbon source for denitrification has achieved successful nitrogen removal up to the regulatory standards (Tanikawa et al., 2020a).

An anaerobic baffled reactor (ABR) is a reactor with multiple compartments consisting of vertical baffles which could effectively be used to minimize the risk of clogging reactors due to a large number of residual rubber particles (Tran et al., 2017; Watari et al., 2017b). Nevertheless, the performance of ABR could be hindered due to the acidic nature and sulphate content of the NR wastewater. In addition to that, chemicals used for pH adjustment would not be economical when it comes to larger wastewater volumes. Hence, the study carried out on the comparison of NaOH and ash from para firewood for pH adjustment of wastewater before the treatment using ABR, could be a suitable alternative as an alkali to maintain the buffering capacity of wastewater (Saritpongteeraka and Chaiprapat, 2008). However, this study would further require research on the increased solids in the subsequent compartments which could be due to the ash content used in pH adjustment.

Moreover, high Zn concentrations reported ranging from 350 to 1500 mg/L in the rubber thread wastewater owing to the chemical addition could also inhibit the anaerobic-aerobic treatment systems. Using sulphide precipitation for zinc as a pre-treatment has revealed that the removal of soluble Zn content to less than 1 mg/L, allowed the anaerobic-aerobic process to remove organic content of more than 96% (Anotai et al., 2007). Rather than the conventional method of hydroxide precipitation, this method has been found superior due to its high efficiency and reliability. Almost all the studies on aerobic-anaerobic reactors have focused on organic and nitrogenous compound removal and many of them have achieved more than 80% contaminant removal. Most of these systems seem to require organic loading capacity improvement seeing that even the anaerobic digestion system by Anotai et al. (2007) which experienced a greater organic load has not achieved the regulatory standards.

3.2.4. UASB reactors and anaerobic digesters

According to the performance summary in Table 5, a considerable amount of research seems to be focused on UASB development seeing a large number of research carried out on the technique. To study the effect of the real nature of rubber wastewater in the formation of sludge granules, Boonsawang et al. (2008) studied the UASB system providing $AlCl_3$ and $CaCl_2$ to enhance the sludge granulation process where $AlCl_3$ has been found to be a more effective supplement. In agreement, Thanh et al. (2016) have also noticed that the use of $AlCl_3$ as a supplement could positively affect granular formation in UASB and further could support higher COD removal while adapting to higher organic loading

Table 5
Secondary treatment of rubber wastewater using aerobic and anaerobic reactors.

Treatment Method	Wastewater Type	Removal Efficiency (%)							Reference
		COD	SS	Turbidity	NH_3–N	BOD	Colour	Other	
Anaerobic baffled reactor (ABR)	Wastewater from NR coagulation process	92.3% [3420 mg/L]	90% [225 mg/L]	–	–	–	–	–	Tran et al. (2017)
ABR	Concentrated rubber latex wastewater – pH adjusted with NaOH	82.71% [5958 mg/L]	–	–	–	–	–	SO_4^{2-} – 96.16% [1819 mg/L]	Saritpongteeraka and Chaiprapat (2008)
	Concentrated rubber latex wastewater – pH adjusted with para wood ash	80.77% [5634 mg/L]	–	–	–	–	–	SO_4^{2-} – 96.60% [1778 mg/L]	
Down-flow hanging sponge (DHS) reactor	Synthetic NR wastewater from an anaerobic-aerobic system	86.8% [280 mg/L]	–	–	83.3% [203 mg/L]	–	–	TN – 79.8% [208 mg/L]	Tanikawa et al. (2019b)
DHS reactor	Effluent of an anaerobic baffled tank from a Ribbed smoked sheet (RSS) processing factory	63.6% [280 mg/L]	20.8% [72 mg/L]	–	85.9% [142 mg/L]	82.7% [202 mg/L]	–	TN – 63.4% [156 mg/L]	Watari et al. (2017a)
ABR and DHS combined system	Synthetic NR wastewater	98% [6110 mg/L]	–	–	–	–	–	TN – 21.2%	Tanikawa et al. (2020a)
BR-UASB-DHS System	NR processing wastewater	98.6% [8430 mg/L]	98% [1470 mg/L]	–	50% [200 mg/L]	–	–	TN – 47.6% [420 mg/L]	Watari et al. (2016)
ABR		92.3% [3420 mg/L]	–	–	–	–	–	–	Watari et al. (2017b)
Open-type ABR (OABR)		94.4% [7520 mg/L]	–	–	18.1% [210 mg/L]	–	–	–	Tanikawa et al. (2019a)
Anaerobic + two-stage bio-contact oxidation cells for Biofortification process		98.7% [3012 mg/L]	92% [453 mg/L]		99.7% [83 mg/L]	98.6% [1315 mg/L]			Jing et al. (2018)
Anaerobic-Aerobic process under bioaugmentation		98.02% [3179 mg/L]	93.11% [262.6 mg/L]	–	96.06% [308.44 mg/L]	98.90% [1567 mg/L]	–	–	Wang et al. (2014)
Anoxic-Oxic process with bioaugmentation using MEM flora		90% [760–2442 mg/L]	–	–	83% [39–70 mg/L]	–	–	–	Wang et al. (2013b)
Anaerobic-Anoxic-Aerobic process under bioaugmentation		98.1% [1997 mg/L]	82.5% [200 mg/L]	–	99.8% [119.98 mg/L]	98.09% [947 mg/L]	–	–	Wang et al. (2013a)
Purple non-sulphur bacteria (PNSB), with fermented pineapple extract (FPE) under micro-aerobic light conditions	Rubber sheet wastewater	91% [2000 mg/L]	75%	–	–	–	–	Total Sulfide – 61%	Kornochalert et al. (2014)
Integrated anaerobic filter and activated sludge system	Rubber thread production wastewater	96.6% [18,219 mg/L]	–	–	–	99.4%	–	–	Anotai et al. (2007)
Two-tank anaerobic digester system	Rubber sheet wastewater	69.23% [18,200 mg/L]	63.16% [66.5 mg/L]	–	–	66.86% [8450 mg/L]	–	TP – 36.74% [92 mg/L] TKN – 35.81% [52.5 mg/L]	Thongnueakhaeng and Onthong (2012)
Up-flow Anaerobic Filter Process (UAFP) with Activated sludge process	Coagulation pretreated Rubber thread wastewater	–	–	–	–	–	–	TOC – 95% [2500 mg/L]	Kida et al. (1997)
UASB with $AlCl_3$ supplement for sludge granulation	NR processing wastewater	96.5% [2741 mg/L]	74% [279 mg/L]	–	–	–	–	–	Thanh et al. (2016)
UASB with $AlCl_3$ supplement for sludge granulation	Concentrated latex wastewater	68% [3350 mg/L]	–	–	–	–	–	–	Boonsawang et al. (2008)
Two-stage UASB and a DHS	NR processing wastewater	95.7% [9710 mg/L]	–	–	–	–	–	–	Tanikawa et al. (2016a)
Two-stage UASB containing an acid tank + UASB reactor	Concentrated latex processing wastewater	82% [4000 mg/L]	92%	–	–	–	–	–	Jawjit and Liengcharernsit (2013)

(*continued on next page*)

Table 5 (*continued*)

Treatment Method	Wastewater Type	Removal Efficiency (%)							Reference
		COD	SS	Turbidity	NH$_3$–N	BOD	Colour	Other	
UASB + Coagu-flocculation + Aeration + Caustic scrubber	Latex processing wastewater	87% [14,733 mg/L]	–	–	–	84% [4433 mg/L]	–	TKN – 87% [911 mg/L] TDS – 69% [4479 mg/L]	Rahman et al. (2021)
UASB	Pre-coagulated Deproteinized NR wastewater	92.2%	–	–	–	95.6%	–	–	Hatamoto et al. (2012)
Up-flow anaerobic fixed film reactor	Synthetic rubber wastewater	98% [6351 mg/L]	–	–	–	–	–	–	Ismail et al. (2020)
Sequencing Batch Reactor	Rubber processing wastewater	95.1%	–	–	92.7%	–	–	TN – 89.5%	Rosman et al. (2014)
	Standards Malaysian rubber processing wastewater	96.5% [1850 mg/L]	–	–	94.7% [49 mg/L]	–	–	TN – 89.4% [248 mg/L]	Rosman et al. (2013)

(Initial parameter values are presented in [] brackets).

Table 6

Secondary treatment of rubber wastewater using adsorption or filtration.

Treatment Method	Wastewater Type	Removal Efficiency (%)							Reference
		COD	SS	Turbidity	NH$_3$–N	BOD	Colour	Other	
Adsorption/Filtration Techniques									
Adsorption by activated carbon prepared using Delonix regia pods	Rubber wastewater	70.65% [5230 mg/L]	–	–	–	–	–	–	Daud et al. (2018b)
Adsorption by Chitosan beads		–	–	–	–	–	71.5%		Daud et al. (2018c)
Adsorption by chemically modified powder made from Delonix regia pods		–	–	–	74.3% [66 mg/L]	–	–	–	Daud et al. (2018a)
Filtration by Hydroxyapatite and lampang clay nanocomposite powder		–	97.67% [106 mg/L]	–	–	99.997% [15,868 mg/L]	–	TP – 100% [218 mg/L] TKN – 100% [448.96 mg/L]	Chankachang et al. (2016)
Adsorption by Granular palm shell-activated carbon	Rubber product manufacturing process wastewater	–	–	–	–	–	–	Zinc – 96% [10 mg/L]	Issabayeva and Dih (2019)

(Initial parameter values are presented in [] brackets).

rates. UASB reactor has also shown a greater reduction in GHG emission when used as a single treatment unit (Tanikawa et al., 2019a).

However, even for integrated systems, rubber particles in the incoming wastewater cause the anaerobic process to hinder and the high concentration of organic matter necessitates an additional aerobic phase to achieve the effluent standards. An integrated system with BR, UASB, and a DHS developed by Watari et al. (2016) could be used to minimize the effect while improving efficiency. Integrated UASB + DHS systems need further improvement on nitrogenous compound removal as the effluent is unable to achieve the regulation standards. However, the two-staged UASB system could give the advantage of reduced energy consumption by 95% due to the ability of biogas recovery and low volumes of excess sludge yield compared to aerated ponds (Tanikawa et al., 2016a). The study done to recover residual rubber using CaCl$_2$ in the coagulation process has been able to recover a methane content of 1.47 Nm^3/m^3/d (Hatamoto et al., 2012). Though the study by Rahman et al. (2021), in which the influent COD value was as high as 14,733 mg/L could not achieve COD removal standards, the caustic scrubbing unit has been successful in achieving a significant reduction of the unpleasant odour to a tolerable limit. However, this treatment sequence has removed the most organic amount compared with other studies on aerobic-anaerobic systems.

Comparatively in an anaerobic-aerobic integrated system, the anaerobic digesters are more efficient than aerobic digesters since after the anaerobic digester successfully treats the wastewater, usually the loading rate to the aerobic digester is low leading to low efficiency. However, this makes it easier to dispose of sludge in the aerobic stage due to low sludge generation. These biological methods are more advantageous than chemical or physical processes to treat wastewater due to their inexpensiveness, simplicity, fewer chemical requirements, being environmental friendly, less energy requirement, less sludge generation/waste and most of the time the by-products are non-toxic. However, high operation duration and inability to successfully handle hazardous chemicals could be limiting factors when implementing them on an industrial scale.

3.2.5. *Adsorption and filter techniques*

Adsorption is a very effective technique in contaminant removal from aqueous solutions. In addition, many alternative low-cost adsorbents have been researched and identified as excellent adsorbents to be used in wastewater treatment because though activated carbon is a superior adsorbent, its material and regeneration costs are very high.

As in Table 6, the use of Delonix Regia pods for Ammoniacal nitrogen and colour removal from NR wastewater has shown impressive performance. However, concerning the effluent COD concentration, it is higher than the specified standards by authorities. Hence, a pre-treatment or polishing stage is required to achieve the discharge limitations for COD from NR wastewater treatment. Further, as a cost-effective method of Zn removal, Issabayeva and Dih (2019) have studied the potential of Zn adsorption using a low-cost palm shell-activated carbon which could be a significant finding. In addition, Nanocomposite filters made using hydroxyapatite and Lampang clay composite have been studied to use as filter materials to treat rubber wastewater. The study has revealed that the filter can successfully remove SS and BOD with more than 97% efficiency. However, the most noticeable finding is that the material had been able to remove TP and TKN concentrations up to a non-detectable level (Chankachang et al., 2016).

Although adsorption and filtration techniques are effective in removing contaminants, their major limitations include the expenses associated with regeneration and/or the safe disposal of contaminated adsorbents or filter materials, without causing any negative environmental impacts. Consequently, additional research is necessary to identify materials that are capable of efficiently removing contaminants and can be reused.

3.3. *Advanced treatment techniques*

The conventional bioprocesses used in wastewater treatment are becoming less and less effective due to the changing nature of the wastewater strength with the increased use of chemicals in the rubber production processes. In addition, these conventional treatment techniques are not effective in the removal of nitrogenous compounds and further, require a considerable land area and longer retention times. Hence, advanced treatment techniques are being suggested by researchers to eliminate issues faced with conventional systems (Tanikawa et al., 2019a). Electrolysis, electrocoagulation, electroflotation, radiation, advanced oxidation processes (AOPs), and membrane technology are some examples of advanced treatment techniques (Nguyen and Luong, 2012). Studies on the use of such treatment systems on rubber wastewater are summarized in Table 7 and Table 8. Most of them have proven highly efficient at the lab scale with simple designs and fewer chemical requirements in accomplishing the discharge standards imposed by the regulating authorities. Though it may be the case, these techniques also have some downsides such as secondary sludge generation, the phase change of pollutants, and high operative costs. Hence further research would be required in making these advanced treatment techniques more economical to be adopted in the field (Ashok et al., 2015).

3.3.1. *Microbial fuel cell (MFC) technique and Electrolytic treatment*

The ceramic separator microbial fuel cell (CMFC) technique is a technique that could be used in rubber wastewater treatment. The chemical energy in the influent substrate is converted to electricity by the anode reaction in the MFC. several studies on this have used biochar derived from rubber tree sawdust as the anode electrode and laccase-based cathode, to make the treatment system more economical. This MFC setup can further be improved using multi-anodes made from bamboo charcoal (Chaijak et al., 2020; Chaijak and Sato, 2021).

Electrolytic treatment of rubber wastewater has been studied and identified as an effective technique that could efficiently remove organic

Table 7
Secondary treatment of rubber wastewater using electrochemical/radiation/oxidation techniques.

Treatment Method	Wastewater Type	Removal Efficiency (%)							Reference
		COD	SS	Turbidity	NH_3–N	BOD	Colour	Other	
MFC/Electrolytic treatment									
Electrolytic oxidation based on in situ hypochlorous acid generation	Latex wastewater	97.9% [3820 mg/L]	–	96.8% [530 NTU]	–	–	–	–	(Krishnan Vijayaraghavan et al., 2008b)
	Standard Malaysian Rubber Process wastewater	97% [2960 mg/L]	–	–	–	95.7% [1380 mg/L]	–	–	(Krishnan Vijayaraghavan et al., 2008a)
Ceramic separator Microbial Fuel Cell (Anode-Rubber sawdust biochar, Cathode-Lacasse based air cathode)	Rubber wastewater	89.77% [1000 mg/L]	–	–	–	–	–	–	Chaijak et al. (2020)
Ceramic separator Multi-electrode Microbial Fuel Cell (Multi Anode-Bamboo charcoal, Cathode-Lacasse based air cathode)		90.05% [3500 mg/L]	–	–	–	–	–	Sulphate – 83.07% [1100 mg/L]	Chaijak and Sato (2021)
Radiation techniques									
Gamma radiation combined with Fenton reagent	Anaerobically treated skim serum wastewater	72% [4508 mg/L]		97% [107 NTU]		88% [815 mg/L]		Sulphide – 100% [235 mg/L]	Abraham et al. (2017)
Advanced Oxidation Processes									
Combination of Fenton reagent and activated carbon adsorption	Raw rubber or latex washing wastewater	95% [1420 mg/L]	–	–	–	–	–	–	Agustina et al. (2017)
Plasma chemical & plasma catalytic process by non-thermal gliding arc technique using TiO_2 photo-catalyst	Plastic and rubber manufacturing wastewater	85.5% [550 mg/L]	–	92% [354 NTU]	–	–	–	–	Ghezzar et al. (2008)
Ferrioxalate-induced solar photo-Fenton process using a plug flow baffle reactor	NR latex wastewater	99% [30,000 mg/L]	96.5% [2132 mg/L]	–	–	99% [10,867 mg/L]	–	–	Ashok et al. (2015)
Coagulation-flocculation + ultra-sonication + sonolytic oxidation using persulfate and hydrogen peroxide	Rubber processing wastewater	91.24% [18,267 mg/L]	–	–	–	–	–	–	Rudra Paul et al. (2022)

(Initial parameter values are presented in [] brackets).

Table 8
Secondary treatment of rubber wastewater using membrane filtration techniques.

Treatment Method	Wastewater Type	Removal Efficiency (%)							Reference
		COD	SS	Turbidity	NH_3–N	BOD	Colour	Other	
Ultrafiltration using Polyacrylonitrile membrane (13% polymer solution)	Spent latex wastewater	–	–	–	–	–	–	TOC >94.5% TS > 92.5%	Bodzek and Konieczny (1994)
Ultrafiltration using Polyacrylonitrile membrane (15% polymer solution)		–	–	–	–	–	–	TOC >96.6% TS > 95.8%	
Ultrafiltration using Polysulfone membrane (16% polymer solution)		–	–	–	–	–	–	TOC >96.9% TS > 95.3%	
Ultrafiltration using Polysulfone membrane (19% polymer solution)		–	–	–	–	–	–	TOC >88.2% TS > 93.2%	Konieczny and Bodzek (1996)
Ultrafiltration using flat sheet Polyethersulfone (PES) membrane (10 kDa)	Rubber glove production wastewater	73.07% [72.41 mg/L]	90.61% [68 mg/L]	96.60% [81 NTU]	15.6% [22.07 mg/L]	–	–	TKN – 5.9% [15.71 mg/L]	Yap et al. (2013)
Ultrafiltration using Polyacrylonitrile membrane	Synthetic rubber wastewater	>99% [3000 mg/L]	–	–	–	–	–	–	Dang et al. (2020)
Ultrafiltration using flat sheet cellulose filter materials (30 kDa)	Rinse wastewater in latex processing	95% [70.7 mg/L]	–	–	–	–	–	TS > 98%	Ersu et al. (2004)
Direct contact membrane distillation using hollow fiber membrane made of organic polyvinylidene fluoride	Rubber processing effluent	–	–	97% [332 NTU]	–	–	–	TOC – 99% [6765 mg/L] TDS – 98.7% [18,710 mg/L]	Mokhtar et al. (2015)
Polyvinyl alcohol (PVA) coated nanohybrid PES-ZnO membrane	NR industry wastewater	82.69%	–	–	57.1%	70.24%	–	TDS – 54%	Kusworo et al. (2019b)
PES-ZnO membrane subjected to UV irradiation and thermal annealing		87.5% [262 mg/L]	–	–	81% [25.6 mg/L]	81.4% [85 mg/L]	–	TDS – 56% [208 mg/L]	Kusworo et al. (2019a)
PES-ZnO membrane subjected to UV irradiation and cross-linked PVA coating		82.6% [262 mg/L]	–	–	57% [25.6 mg/L]	82.11% [85 mg/L]	–	TDS – 51% [208 mg/L]	Kusworo et al. (2021)
PES-SiO_2 membrane modified by Polyethylene glycol (PEG) and subjected to UV irradiation	NR wastewater – Coagulation treatment discharge	87%	–	–	89%	–	–	TDS – 52.13%	Kusworo et al. (2020a)
Polysulfone membrane doped with nano-TiO_2 particles	NR wastewater	87.88% [273 mg/L]	–	99% [32 NTU]	88.79% [18.68 mg/L]	–	–	TDS – 14.03% [297 mg/L]	Kusworo et al. (2020b)
Nanofiltration membrane with polyamide selective layer on polysulfone support	Rubber tubing extrusion wastewater	93.4% [30,260 mg/L]	–	–	–	–	–	TOC – 87.17% [5709 mg/L]	Lopes et al. (2013)
PAN-based hollow fiber membranes incorporated with graft copolymers bearing hydrophilic PVA and PAN segments	NR wastewater	29–38% [1682 mg/L]	–	>99% [622 NTU]	–	–	>97% [2633 pt-Co]	TOC – 14–32% [550 mg/L] TDS – 8–11% [2.52 mg/L]	Nazri et al. (2015)
Nanofiltration using NF270 module	Rubber wastewater	>95% [14,829 mg/L]	–	–	–	–	–	–	Xin et al. (2013)

(Initial parameter values are presented in [] brackets).

matter with the use of hypochlorous acid generation inside the treatment unit. Optimum conditions for the unit were found to be an initial pH of 4.5, sodium chloride content of 3%, and a current density of 74.5 mA/cm^2. However, during this electrochemical oxidation process, other than the disinfection process of wastewater, excess chlorine, chlorinated organics, and excess salt could be generated which need further processes for their removal. This process has recorded energy requirements between 30 and 50 Wh/L at optimum conditions. (Krishnan Vijayaraghavan et al., 2008a; 2008b).

3.3.2. UV, ozone radiation, and gamma-ray treatments

Despite high capital cost being a major drawback, UV, ozone radiation and gamma ray treatment present several advantages when used in the treatment sequence including, the ability for the process to be carried out in ambient global conditions, decomposition of volatile and semi-volatiles organic compounds in the aqueous phase, no requirements of extra chemicals, no requirements of removing excess of toxic compounds prior to discharge and the process transforms the refractory organic pollutants into highly degradable products (Ye et al., 2010).

The use of radiation treatment is an emerging technique for high-strength industrial wastewater. Abraham et al. (2017) have studied the effect of gamma rays in combination with Fenton reagent in skim serum wastewater treatment. However, no significant removal efficiency has been observed in organic and nutrient removal in raw wastewater treatment when studied using various reagents and gamma radiation combinations. However, when anaerobically treated wastewater was subjected to treatment, organic and sulphide removal had been high despite the low nitrogen compounds removal. According to Hadiyanto et al. (2020) also, the combination of UV/Ozone process to treat rubber wastewater is not suitable for the removal of TN and phosphorous adequately, though it could successfully remove organics efficiently. The study by Park et al. (2008) further confirms that gamma-ray treatment is not capable of removing toxic compounds from rubber wastewater adequately as it breakdown into various other forms which might need to be treated using a treatment process like filtration.

3.3.3. *Advance oxidation processes (AOPs)*

To eliminate the limitations in ozonation methods, it has been studied coupling the ozonation method with Fenton reagents. Hydroxyl radicals produced the by Fenton reagent react faster than ozone and H_2O_2 as oxidants. The further improved advanced oxidation process was studied by Ghezzar et al. (2008) where pulsed high voltage is applied to generate highly active oxidants. This process is known as Non-Thermal Plasma (NTP) and it comprises a gliding arc discharge [glidarc] system device. In this study, TiO_2 addition has further increased the treatment efficiency. Though these methods could solve many issues with ozonation treatment while giving reusable quality treated water, according to Ashok et al. (2015), the cost of the Fenton reagent method could also go up to \$ 85/m^3 when the system is used for treating 5 m^3 of wastewater per day. Nevertheless, because of the hazardousness of the sludge produced by the Fenton process, Gamaralalage et al. (2019) studied the possibility of reusing the sludge in the Fenton process as a Fe source and reported that it could be an environmentally viable and economically promising method. Despite AOPs being able to break down a wide range of refractory chemicals, these methods are costly, require chemicals and complex operations, and may occasionally produce secondary sludge where disposal could be an issue.

3.3.4. *Membrane filtration*

Membrane-based treatment processes are in trend to treat high-strength wastewater due to their effectiveness, where the treated effluent could be effectively used in land irrigation and the production process itself according to the level of purification. Studies suggest that ultrafiltration (UF) membranes are capable of removing contaminants such as TOC and TS with greater efficiency while not causing any secondary contamination of the effluent by used chemicals. Furthermore, they can effectively be operated at ambient conditions thus leading to lower energy consumption. In addition, studies have also proven that membrane bioreactor (MBR) systems with UF flat sheet membrane alone could treat nitrogen in high-strength skim latex wastewater greater than 60% without integrating with an anoxic phase (Sulaiman et al., 2010). However, UF membranes are not capable of removing trace metals as their main purpose is to separate macromolecules. Therefore, Nanofiltration (NF) or reverse osmosis (RO) systems are recommended which involve rejections in the ionic range (Yap et al., 2013). In compliance, a comparative study using UF ceramic tubular membrane and an NF flat sheet membrane suggested that the NF treatment unit could efficiently treat high-strength rubber wastewater with reduced cost for energy (Lopes et al., 2013).

Direct contact membrane distillation (DCMD) technology using polyvinylidene Fluoride (PVDF) hollow fibre membrane resulted in producing an effluent with extremely low-level concentrations of several contaminants. Though this may be the case, similar to other membrane systems, membrane fouling has been a serious issue because of which the flux was severely declined over time leading to low permeate production rates (Mokhtar et al., 2015).

Nanomaterial blending to enhance the membrane structure and PEG and UV irradiation to enhance the hydrophilic character of membranes have been the focus of many research carried out regarding the improvement of membrane technology (Abdelrasoul et al., 2017; Kusworo et al., 2021, 2019b; Kusworo et al., 2020a; Kusworo et al., 2020b). Developments have been done to improve the membrane's perm-selectivity properties. The PVA coating has been found to improve the membrane's anti-fouling properties while reducing the adsorptive foulant deposition. ZnO modification could significantly improve the structural and morphological properties while thermal annealing rearranges the molecular structure of the membrane polymers to increase crystallization leading to increased membrane rejection. However, it is observed that increasing thermal annealing time, increased duration of UV irradiation and unnecessarily high concentrations in PVA coating lead to reductions in the permeate flux (Kusworo et al., 2019b). A study to minimize membrane fouling has been conducted with PAN-based hollow fibre membranes by incorporating graft copolymers which consist of PVA and PAN segments has been reported to achieve more than 75% flux recovery after 1st and 2nd treatment runs when cleansed using simple hydraulic cleansing methods. Even though the membrane could achieve high removals for turbidity and colour, organic matter and TDS removal were argumentatively low when compared with other studies. This observation could be due to the larger pore size of the membranes which could have been a result of the surface modification method (Nazri et al., 2015).

3.4. *Currently used rubber wastewater treatment practices in Sri Lanka*

Around 40% of the rubber glove manufacturing industries in Sri Lanka which are generating more than 100 m^3/day wastewater volumes, use the conventional chemical treatment (coagulation-flocculation) processes for rubber wastewater treatment while some industries use an integration of chemical and biological processes. Only a handful of manufacturers use biological treatment as the sole treatment technique. As these manufacturing companies are managed under the industrial zones targeting the export of products, only the preliminary treatment is conducted on-site. However, these treatment plants have faced several issues due to not being able to handle the chemical dosing and mixing properly during the treatment process which had sometimes resulted in effluent quality not being up to the specified standards. After the pre-treatment, the wastewater is sent to the centralized wastewater treatment plant which commonly uses the treatment sequence of a grit chamber, aeration lagoon, oxidation ditch, settling tank, drying beds, and maturation ponds to treat the wastewater up to the discharge guidelines imposed by the Central Environmental Authority in Sri Lanka.

Even though many of the lab-scale studies have tried to experiment with techniques that generate a low sludge yield, when it comes to sludge management at the industrial level, the sludge generation varies from 1 - 10 tons/month depending on the type of production. In Sri Lanka, the most commonly used sludge disposal method is incineration while sludge drying beds, landfilling and industrial zone dump yards are also used for the disposal of the sludge generated in the rubber wastewater treatment process.

4. Achieving targets of SDGs in rubber wastewater treatment plants

So far, the content was focused more inclined with achieving UN-SDG 6 and part of SDG 12 where the UN proposes to improve water quality by the reduction of pollution and elimination of dumping and minimization of the release of hazardous chemicals and materials to improve water quality (Target 6.3 & Target 12.4). Henceforth, the paper will discuss more on how the rubber industry could support achieving several other goals and targets of UN-SDGs.

With the latest trend being sustainable development, the rubber industry is at a turning point to adopt cleaner production techniques, focusing on water usage and waste generation minimization, recycling of water using advanced treatment techniques, resource recovery from waste and wastewater, and other necessary actions (Mokhtar et al., 2015). With almost all rubber crop planting countries making plans for future expansion of the rubber industry, water stress is becoming one major factor affecting the industry due to its large volume requirement for daily production processes. Therefore, sustainable approaches to water management need to be considered. Hence, this paper reviews some of the studies carried out on the sustainable use of waste products generated in the rubber industry, and Supplementary Data – Fig. S4 gives a summary of them.

4.1. Reuse of treated wastewater and minimization of wastewater generation

As there is a need to measure several typical parameters before the discharge of the treated wastewater, Kumlanghan et al. (2008) suggested using a microbial sensor which uses an oxygen electrode, to detect BOD in a shorter time rather than waiting for 5 days. This method could easily obtain BOD of the effluent of an anaerobic reactor which treats wastewater from the concentrated latex process. Hence, this approach could minimize the environmental cost which could have been caused by the unintentional discharging of the wastewater which is not treated up to standards, from the treatment plant during the time of testing of 5 days. This method could further assist in SDG Target 6.3 by controlling the untreated proportion of industrial wastewater outflow.

The suitability of latex wastewater for irrigation purposes after ultrafiltration treatment has been suggested by several researchers and further, they have studied that this would not cause any groundwater contamination. In addition, the treated water could also be used for rinsing purposes in the latex concentration process owing to the low total solids concentrations (Dang et al., 2020; Ersu et al., 2004). It has been reported that UV/Ozone treated wastewater could be successfully applied *in Spirulina platensis* microalgae cultivation because of the capability of supplying as a food supplement with sufficient nitrogen and phosphorous nutrients. In this study, the microalgal growth rate has been recorded as 0.3 day^{-1} hence, recommended to be used in large-scale microalgae cultivation bioprocesses to minimize the production costs (Hadiyanto et al., 2020).

Leong et al. (2003) suggested several approaches which could be used in water conservation, recycling, and wastewater minimization in a rubber factory. Recycling some process water until the end of its useful age, separating sewage and stormwater runoff from processing effluent using pipelines, and reusing this type of water for processing, cleaning or washing are some of the methods suggested in the study. SDG Targets 6.4 and 12.5 indicating the increase in water use efficiency can be addressed by improving these methods to reuse the treated/untreated wastewater for different purposes inside the rubber manufacturing factories.

A study by Owamah et al. (2014) has found that water lettuce-based waste stabilization pond-treated effluent liquid can be used as biofertilizer because of their nutritive values supporting the increase of the yield in crops like maize. In addition, the study also revealed that the resulting water lettuce biomass from treatment units can be used as forage for animal feeding.

Another research has also revealed that wastewater effluent from cooperative rubber factories could be used to improve soil properties instead of inorganic fertilizers, to irrigate vegetables, rubber plantations, and crops like rice due to the available nutrients (N, P, K) content in the effluent but in some occasions, it may be necessary to add chemical fertilizer or manure (Chaiprapat and Sdoodee, 2007; Robert et al., 2007; Waizah et al., 2011). Carrying out further research on producing value-added products as outcomes from the waste generated covers several UN-SDG targets such as Target 9.2 and 9.5 and further, these steps could increase the overall value of the industry in the global context.

4.2. Biogas production for energy

Anaerobic digesters used in the treatment process can be seeded with starter seeds collected from full-scale anaerobic treatment units treating cassava starch, palm oil mill, and swine manure collected from a swine farm. Studies have recorded that highly polluted rubber wastewater treated in such digesters could be used to produce CH_4 at rates 12.37, 8.95, and 8.32 $mLCH_4/gVSS$ per day, respectively (Chaiprasert et al., 2017). Thongnueakhaeng and Onthong (2012) observed that the biogas produced from a full-scale anaerobic digestion system used in an air-dried sheets production wastewater treatment system could be used for cooking for about 2 h per day as the biogas production was high as 360 L per day in a 0.8 m^3 reactor with a biogas production rate of 0.57 m^3-gas/kg $COD_{removed}$. Improving these methods could ultimately increase the share of renewable energy in the total final energy consumption to support achieving UN-SDG target 7.2. Nevertheless, though there are suggestions that mixing latex wastewater with palm oil mill effluent to reduce its toxicity could enhance biogas production, an important study by Yingthavorn et al. (2016) has proven that this combination would cause the whole treatment system to fail caused by the monitoring system failure. Hence, adapting such methods in enhancing the efficiency of treatment units need to be further studied under controlled condition before implementing on a larger scale.

However, high concentrations of ammonia and sulphuric acid in rubber wastewater streams could inhibit the methanogenic activity in the anaerobic digestion unit eventually leading to low-quality biogas production. Thus, the use of a bio-filtration system containing sulphur oxidizing bacteria immobilized on granular activated carbon as packing material has been studied for H_2S removal from methane. Sulphur oxidizing bacteria cultures had been studied as pure cultures with *Alcaligenes faecalis* T307 and as mixed cultures. A system containing pure culture has been able to achieve complete removal of H_2S in the long run even at high inlet concentrations ranging from 200 to 4000 ppm (Rattanapan et al., 2009, 2010, 2011). This finding is important as this biogas pre-treatment is essential to minimize the cost of the energy recovery system and if H_2S in biogas is not eliminated before combustion, that could cause corrosion in cogeneration engines and microturbine units.

4.3. Bioelectricity generation

Similar to biogas production in achieving energy efficiency, bioelectricity can also be generated using rubber wastewater as an anolyte in microbial fuel cell technology. CMFC with rubber tree sawdust-derived biochar anode and laccase-based air cathode had been able to produce a volumetric power density of $3.26 \pm 0.08\ \mu W/m^3$, the volumetric current density of $3.20 \pm 0.07\ mA/m^3$ and system internal resistance of 1002 Ω while MFC with bamboo charcoal multi-anode and laccase-based cathode had been able to produce volumetric power density of $711.23 \pm 9.76\ mW/m^3$, the volumetric current density of $843.33 \pm 5.77\ mA/m^3$ (Chaijak et al., 2020; Chaijak and Sato, 2021). Nevertheless, even though the power generated in this method could be used for the treatment process itself, these studies need to be further developed to achieve a higher electrical power outcome that is capable of using in other processes as well.

5. Challenges and future aspects

With the increasing demand for NR and rubber-based products, it can be predicted that the rubber processing industry would be demanding higher and higher volumes of water for its production in the future. Growing water stress and scarcity issues would be the most challenging aspects of the sector. Hence, adapting sustainable approaches in the production processes would be vital.

Furthermore, all these treatment techniques researched have ended up with commercially valuable by-products such as biogas and nutrient-rich sludge. Studies would be encouraged on the development of effective and economic recovery methods for biogas and the applicability of biogas in rubber processing plants themselves with the upgrades required in existing treatment techniques. As it can be noted that for high-strength wastewater, organic and nutrient removal cannot be achieved using a standalone treatment process, the adaptation of an integrated process could be recommended. However, this should be planned after obtaining a thorough understanding of the contaminant removal mechanisms of each process.

Though the literature provides bioaugmentation and bioremediation as good solutions, only a few studies have focused on studying the removal efficiencies using those processes and the effect of co-existing pollutants on some specific contaminant removal bacteria, for instance, how the organic degrading bacterial activities will be inhibited by high concentrations of ammonia in skim serum latex processing wastewater. Hence, further research should be carried out on investigating the inhibitory and competitive removals of contaminants using these processes.

Even though some heavy metals such as Zn are essential macronutrients, excessive levels of these heavy metals released into water streams may lead to toxicity concerns accumulating in aquatic organisms. Therefore, it is highly recommended that a toxicology assessment with regard to the rubber wastewater quality be carried out to get a clear overview. Water quality index, heavy metal pollution index, and heavy metal evaluation index are some approaches that can be considered to assess the heavy metal impact on the water quality and water pollution while hazard index and hazard quotient can be used to identify the adverse health effects such as carcinogenic effects that may arise from heavy metals (Topaldemir et al., 2023; Yüksel et al., 2021).

Further, many successful modifications to conventional treatment techniques and more advanced technologies have been researched which could be used to treat rubber processing wastewater up to reusable quality for agricultural purposes or even for reuse in the production process. Nevertheless, these studies are more or less done on a laboratory scale. Further studies would be required to make these technologies more economical to be adapted in larger scale corporations with a small footprint and long-term application.

6. Conclusions and recommendations

The discharge of untreated wastewater from rubber processing industries that contain high-strength pollutants has a harmful impact on both aquatic and terrestrial ecosystems, leading to water quality deterioration. The lack of adequate treatment methods for rubber industry wastewater, particularly from processes like NR Latex production, results in significant water pollution caused by high concentrations of COD and nitrogenous compounds resulting from the use of chemicals in the production process. Therefore, it is imperative to implement advanced treatment methods for rubber industry wastewater to effectively remove pollutants and meet stringent environmental regulations set by the authorities in respective countries. Thus, this paper reviewed the studies conducted on improving rubber wastewater treatment techniques. Although various advanced treatment methods have been successfully investigated that possess both advantages and drawbacks on their own, selecting a treatment sequence with pre-treatment, secondary, and polishing stages for each processing industry depend on several factors where cost and meeting the regulations by the used treatment sequence play major roles. Nonetheless, it is important to assess the feasibility of lab-scale work to scale them up for industrial use. Moreover, given that there has been a number of studies to assess the reusability and resource recovery from rubber wastewater, and with the increasing importance of the concepts of sustainability, future research should be focused on enabling sustainable development and cleaner production techniques to the rubber industry that are both cost-effective and environmentally sound.

Author contributions

W.S.M.S.K. Wijerathna: Conceptualization, Literature search, Data curation, Writing – original draft, T.I.P. Wimalaweera: Conceptualization, Literature search, D.R. Samarajeewa: Supervision, Writing – review & editing, L.M.L.K.B. Lindamulla: Literature search, R.M.L.D. Rathnayake: Supervision, Writing – review & editing, K.G.N. Nanayakkara: Supervision, Writing – review & editing, V. Jegatheesan: Writing – review & editing, Yuansong Wei: Writing – review & editing, K.B.S.N. Jinadasa: Conceptualization, Supervision

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2023.139512.

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