Oil Palm Industry Economic Journal Vol. 24 (1) March 2023 p. 11-19
DOI: https://doi.org/10.21894/opiej.2024.02

RESEARCH TRENDS IN PALM OIL MILL EFFLUENT (POME) WASTEWATER TREATMENT USING BACTERIA IN MALAYSIA: A SYSTEMATIC REVIEW

NURUL ASMAK MD LAZIM[1]*; ZAHARAH IBRAHIM[2]* and NURAIN MOHD NAZIR[3]

ABSTRACT

The development of POME wastewater treatment using the appropriate bacteria and biological treatment will result in a certain level of management and laboratory abilities that can affect the treatment's overall effectiveness. POME wastewater treatment requires effective microbes to adapt to shifting possibilities and demands. However, little is known about how is the treatment defined, workings, and its biological approaches with POME wastewater treatment, both on a pilot and larger scale. Not to add, an explanation of wastewater treatment from an economic standpoint as well. This study aims to review POME treatment trends and the relationship between bacteria and treatment, as well as how the biological influences treatment. A descriptive content analysis approach was used to go through 2054 reviews, conceptual, empirical, and commentary pieces that were published in journals from Scopus and Web of Science. Every pertinent piece of information was taken out of each article and examined. Excel software was used to analyse the data that was taken from the publications. Economic view also included. Results revealed that, after removing extraneous material from 2054 articles, only three publications specifically addressed bacterium species and Malaysian scholars. Parabacteroides, Bellilinea, Levilinea, Smithella, Prolixibacter, *and numerous other bacteria are among those mentioned in the publications. Some improvements have been observed before and after treatment, and the presence of bacteria did have a significant influence on the chemical reaction, which is evidence of POME treatment. To sum up, the paper will contribute to the global knowledge base and recent efforts to improve the current situation (too long HRT), particularly for new research with perspective approaches (biological treatment) to the field.*

Keywords: bacteria, POME, treatment, trends, wastewater.

Received: 17 November 2023**; Accepted:** 11 March 2024**; Published online:** 26 March 2024.

INTRODUCTION

According to calculations made during the milling process based on 2.5 m^3 of raw Palm Oil Mill Effluent (POME) generated, a total of 43.29 million m^3 of raw POME were created annually from a significant amount of water used in the processing (MPOB, 2016; Zainal *et al.*, 2017). Wu *et al.* (2009) reported that to process 1.0 t of crude palm oil (CPO), it would require 5.0 to 7.5 t of water, with the remaining 50% of this water ending up as wastewater effluent. It is reported that in 2023 itself, Malaysia's total CPO production reached 18.55 million tonnes, 0.53% higher than a year ago (Palm Oil Analytics, 2024). As a result, the amount of water required in the process keeps increasing. Raw POME is an additional useful biomass source. It is a thick, brownish liquid effluent with high organic content and significant

[1] Department of Bioprocess & Polymer Engineering, Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia.

[2] Department of Biosciences, Faculty of Science, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia.

[3] School of Biosciences, University of Sheffield, Sheffield, S10 2TN, United Kingdom.

* *Corresponding author's e-mail: nurulasmak89@gmail.com and zaharah@fbb.utm.my*

solid content that has the indirect potential to contaminate the environment, especially the atmosphere and waterways. Raw POME is an acidic effluent with a very low pH of 3.5 to 4.2, high chemical and biological oxygen demands (COD and BOD), and high total suspended solids (TSS) of 51 000, 25 000, and 18 000 mg/L, respectively (Zainal *et al.,* 2017). It required mill operators to pay a high fee, and handling the waste was very challenging (Madaki and Seng, 2013). Therefore, the Department of Environment (DOE), Malaysia, adopted the Environmental Quality Act (EQA) 1974 and set regulatory limits for the discharge of POME into the environment in order to control and reduce the impact of pollution on the environment (Mohamad *et al*., 2021).

Ponding systems are a common industrial POME treatment approach; however, they have an economic disadvantage due to their requirement for vast land area (30-45 acres) and long hydraulic retention time (HRT) (100-160 days). Here, it is necessary to develop low-cost materials and make use of materials that are already available so that they can be used more profitably on an industrial scale. Research interest in the alternative production strategy to partially replace the outdated open-ponding system has increased as a result of the aforementioned issues. Particularly for the biological therapy of POME in the presence of microbial cultures such as bacteria, fungus, yeast, microalgae, and others, which have been the focus of numerous recent studies (Mohamad *et al*., 2021).

A systematic review is an examination of a well-defined research issue that uses specific and systematic procedures to find, evaluate, and critically assess pertinent studies, as well as gather and process data from the studies that are part of the review. The results of the included studies may or may not be analysed and summarised using statistical techniques (meta-analysis). Meta-analysis is the use of statistical methods in a systematic review to combine the findings of the included research (Moher *et al.,* 2009).

For this study, three primary components comprise the conceptual framework that the authors developed: Methodology, conceptual model, and topical foci. The primary themes or subjects covered in the examined papers are referred to as topical focuses. The authors first determined which subjects-such as organisms, biological treatment, *etc.* frequently appear in other recent studies on POME treatment before compiling a list of such subjects. The list of topics was completed at the end of the analysis by iteratively adding more as needed. The second part of the authors' framework focuses on the conceptual models used in the studies that are being examined. A methodology component, which deals with the tools and techniques used in methodological research, wraps up the authors' conceptual framework. This dimension includes both the cultural type (single or mixed) and the strategy.

This study sought to answer the following research questions by synthesising and reviewing the empirical literature on bacteria and biological trends related to POME wastewater treatment in Malaysia;

- RQ1. What are the trends in POME wastewater treatment in Malaysia using bacteria species?
- RQ2. What is the relationship between the trends and POME wastewater treatment?
- RQ3. How is the influence of these trends on POME wastewater treatment in Malaysia?

THE ECONOMICS OF BIOLOGICAL TREATMENT METHOD

In tropical nations, particularly those in Southeast Asia, the palm oil industry has emerged as the primary driver of economic growth. Recent years have seen an increase in palm oil production worldwide, which reached 72 million tonnes in 2018 from roughly 68 million tonnes in 2017. With 84.0% of global production at that time, Indonesia and Malaysia were the world's top exporters of palm oil. From 24.88 million tonnes in 2018 to 27.88 million tonnes in 2019, the total amount of oil palm products exported from Malaysia climbed by 12.1%. However, it was said that the drop in global trade prices resulted in a 4.0% fall in overall export earnings to RM64.84 billion (Kristanti *et al.,* 2021).

The biological treatment method that has been available in Malaysia for the past 20 years to cure POME consists of facultative, anaerobic, and aerobic pond systems. The majority of palm oil mills have used anaerobic digestion as their main method of treating POME. For treatment, more than 85% of Malaysian palm oil mills have chosen to use ponding systems; the remaining mills have chosen to use open digesting tanks. These techniques, which call for lengthy retention periods and extensive treatment areas, are recognised as traditional POME remediation techniques (Abdurahman *et al.,* 2013).

The evaporation method, membrane treatment systems, and aerobic treatment are the currently available alternatives for treating POME. Anaerobic digestion has a bigger benefit over the other alternative methods in terms of energy need for POME treatment operation since it does not require energy for aeration (Haris, 2006; Soo *et al.,* 2022; Vijayaraghavan *et al.,* 2007) (*Table 1*). Moreover, methane gas (CH_4), a value-added byproduct of digestion that the mill can use to increase Certified Emission Reduction (CER) revenue, is produced by the anaerobic POME treatment. For instance, a palm oil mill processing 30 t of FFB/hr quoted a capital cost of RM750 000 for an open digesting tank for POME treatment without land application. The system's estimated in 2006 capital cost is USD370 272, according to the Chemical Engineering Plant Cost Index. This is clearly more advantageous than other treatment methods in terms of capital cost when compared to the membrane system's cost for POME treatment at RM3 950 000 for a palm oil mill processing 36 t of FFB/hr (Abdurahman *et al.*, 2013).

Anaerobic treatment has two drawbacks: A lengthy retention period and a lengthy start-up period. While the lengthy start-up period can be reduced by using granulated seed sludge, using seed sludge from the same process, or keeping the high-rate anaerobic bioreactor at a suitable pH and temperature for the growth of bacterial consortia, the issue of long retention times can be resolved by using these bioreactors (Abdurahman *et al.*, 2013).

METHODOLOGY

This work complies with the recommendations for conducting systematic reviews. First, a systematic review study is used to identify the main areas of interest, research questions, and objectives using this framework. The next stage is to find, pick, assess, and examine pertinent publications using a conceptual point of view. The sources of the data are then discussed, along with the procedures used for analysis and synthesis. Finally, it discusses the implications, limitations, and conclusions.

Data Collection and Analysis

Identification of sources. For this section, the authors chose to use the Web of Science (WoS) database and Scopus to access the publication. The evaluation period is not limited, although the authors concentrated on studies published between 2019 and 2023, which is five years later. The following search term was chosen because it yielded the most representative data set out of all the ones they attempted searching for in the Scopus and WoS databases:

Scopus:

i) TITLE-ABS-KEY(palm oil mill effluent AND treatment)
ii) TITLE-ABS-KEY (palm AND oil AND mill AND effluent AND treatment) AND PUBYEAR > 2018 AND PUBYEAR < 2024 AND (LIMIT-TO (SUBJAREA, "ENVI")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (EXACTKEYWORD, "Palm Oil Mill Effluents") OR LIMIT-TO (EXACTKEYWORD, "Wastewater Treatment")) AND (LIMIT-TO (AFFILCOUNTRY, "Malaysia"))

WoS:

i) ALL = (palm oil mill effluent AND treatment)
ii) Results for palm oil mill effluent AND treatment (All Fields) and Review Article (Document Types) and 2023 or 2022 or 2021 or 2020 or 2019 (Publication Years) and Review Article (Document Types) and English (Languages) and Environmental Sciences Ecology (Research Areas)

TABLE 1. ADVANTAGES AND DISADVANTAGES OF VARIOUS TREATMENTS

Treatment	Efficiency	Advantages	Disadvantages
Evaporation method	85.00%	The process' solid concentrate can be used as a feedstock for the production of fertiliser.	High usage of energy.
Membrane treatment systems	99.03%	Reduced space needed for membrane treatment plants, constant and high-quality water quality after treatment, and the ability to disinfect treated water.	Membrane fouling, short membrane life, and high cost in comparison to traditional treatment.
Aerobic treatment	57.00%, 45.00%, 38.00%, 30.00% and 27.00%	Retention period shorter and more efficient for managing harmful wastes.	Because aerobic sludge requires more energy (aeration) and inactivates pathogens more slowly than anaerobic sludge, it is not appropriate for use on land.
Anaerobic digestion	93.90%	Reduced energy needs (no aeration), the production of methane gas as a valuable byproduct, and the possibility of using the process's created sludge for land uses. Does not require energy for aeration. Cheap.	Long retention period and huge space needed slowly start traditional digesters (granulating reactors).

There were 881 research and review articles in WoS and 1173 in Scopus as a result of this search. The authors filtered and examined every article to remove those that did not fit the field. The data set did not include the out-of-scope articles that focused largely on a range of other disciplines, like engineering, chemical engineering, and many others. Articles pertaining to environmental sciences are the only ones chosen. As a result, there were 114 articles altogether in the data set that was derived from the WoS (22) and Scopus (92) databases. The authors then went through each article's title and abstract to find those that were co-authored or written by Malaysian academics within the same time frame. Using this method, 3 (Scopus) and 5 (WoS) articles were found. For these 8 publications, inclusion and exclusion criteria were used. The inclusion criteria set by the authors are founded on studies conducted by Malaysian scholars, studies of Malaysian organisations, and studies with bacteria for treatments. Research on other nations, research on other microorganisms, and research on other materials outside the scope of biological treatment are the exclusion criteria. Three articles in total that were closely related to bacteria, POME, and studies conducted in Malaysia were included in the review after merging the two data sets and eliminating any overlapping ones (*Figure 1*).

Data extraction. This stage involved extracting from each publication the data pertinent to the authors' study questions (3 articles). A spreadsheet was used to compile the extracted data. For instance, in the "research with bacteria" column, single bacteria as 1, double bacteria as 2, and mixed bacteria were scored as 3. After going over each article's content, the authors created different lists of codes. After that, the two lists were compared, and the differences were talked about. In cases where there was a disagreement, the best category for each article was chosen before data analysis by taking into account the views of subject-matter experts.

Data analysis. The data analysis procedure used Excel. Every research question was addressed in light of every discovery. To find trends and patterns of knowledge production for the relevant research from this developing region, a review of data analysis was carried out. The objective was to expedite the process of formulating suggestions for novice investigators who possess the suitable generation and historical context. Despite the fact that this study was restricted to research conducted in Malaysia, we compared it to other recent evaluations of relevant literature from across the world.

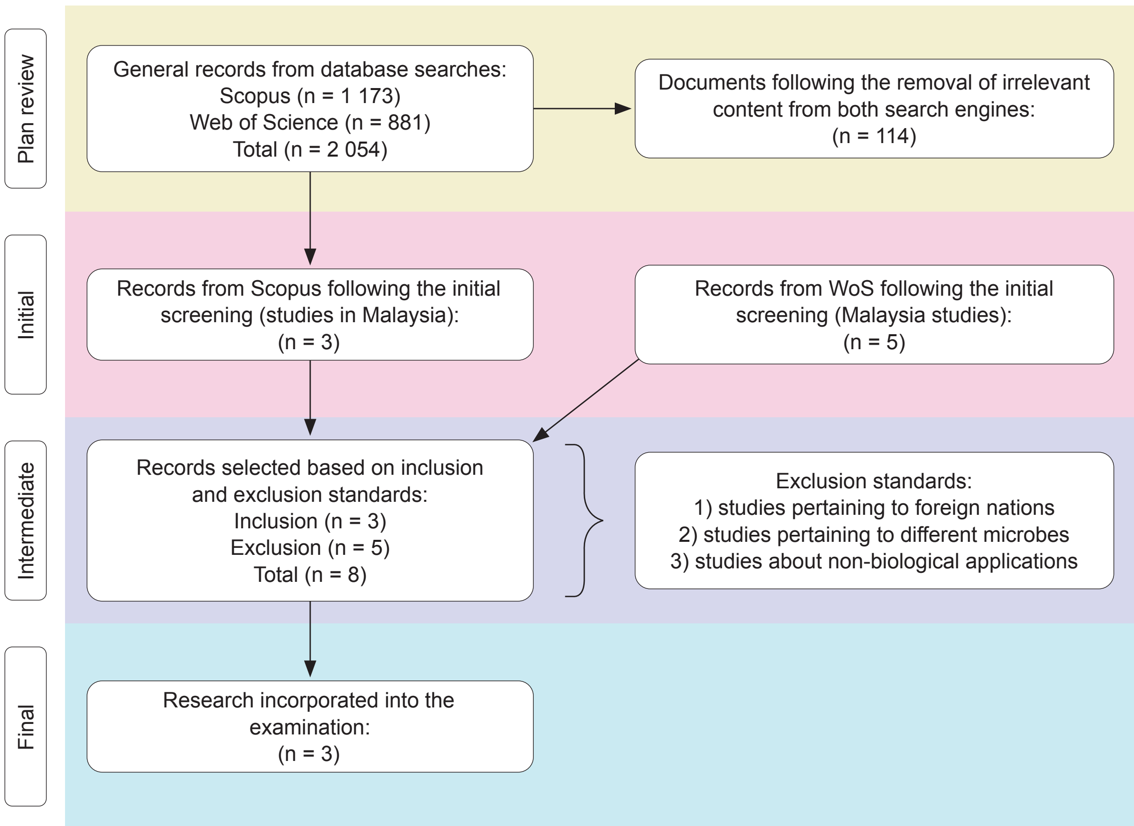

Figure 1. Research flow in this study.

RESULTS AND DISCUSSION

From the authors findings, only three articles from both Scopus and WoS are reported and mentioned specifically on bacteria species and POME treatment, especially from Malaysia's scholars. Others are explained about POME treatment using bacteria or microorganisms in general. Therefore, the authors only explained the research trends of bacteria species in POME treatment based on three articles and only responded to their research question. Otherwise, the authors will discuss and add on additional information when necessary to support the findings. The authors believe the updated POME treatment research trends, specifically with bacteria species, can offer beneficial information for future research improvement.

In response to the authors research questions, the review found that:

- R*Q1. What are the research trends of POME wastewater treatment in Malaysia using bacteria species?*

After excluding unrelated papers (based on publication type, language, field, year, *etc.*), the search yielded 2054 articles that examined POME wastewater treatment utilising bacteria trends in Malaysia. The total number of articles was then reduced to 114. Following a preliminary screening, eight papers were compared to the inclusion/exclusion criteria that the authors could obtain from the abstract and title. Three empirical research studies were left, and these three studies served as the main subject of this review. Nevertheless, the authors choose to talk about these three papers that particularly addressed the species of bacteria used in POME treatment in Malaysia after carefully examining all the article's detailed material (*Table 2*).

From *Table 2*, it can be seen the bacteria trends in POME wastewater treatment in Malaysia as reported in 2022 are *Parabacteroides, Bellilinea, Levilinea, Smithella* and *Prolixibacter; Nitriliruptor, Delftia, Filomicrobium, Steroidobacter* and *Ohtaekwangia; Steroidobacter, Nitriliruptor, Anaeromyxobacter, Filomicrobium* and *Filomicrobium; Devosia yakushimensis* and *Desemzia incerta*; *Planococcus rifietoensis* that were found in POME anaerobic sludge. Meanwhile, in 2020, the bacteria trends are *Bacillus velezensis, Pseudomonas aeruginosa (strain IASST201), Achromobacter xylosoxidans, Streptomyces* sp. *Gansen* and *Cellulomonas* sp. *Okoh* have been used together with bioflocculant. In the same year of 2020, *B. subtillis* mixed with *Methanosarcinales* and *Methanobacteriales* and combined with bio-augmentation to treat POME wastewater were also reported for the treatment (*Table 2*). All studies used mixed culture approach to treat POME wastewater (pilot scale).

To summarise, from these three articles, the authors found that the research trends specifically mentioned on bacteria species in POME wastewater treatment whether in the mixed or single culture form, in pilot scale, within review and research articles, direct treat or changing the waste to beneficial form are *Parabacteroides*, *Bellilinea, Levilinea, Smithella, Prolixibacter, Nitriliruptor, Delftia, Filomicrobium, Steroidobacter, Ohtaekwangia, Steroidobacter, Nitriliruptor, Anaeromyxobacter, Filomicrobium, Filomicrobium, D. yakushimensis, D. incerta*, *P. rifietoensis, B. velezensis, P. aeruginosa (strain IASST201), A. xylosoxidans, Streptomyces* sp. *Gansen* and *Cellulomonas* sp. *Okoh, B. subtillis* mixed with *Methanosarcinales* and *Methanobacteriales* and combined with bio-augmentation (from year 2020-2022).

- *RQ2. What is relationship between the research trends and POME wastewater treatment?*

In Malaysia, POME anaerobic sludge is easily accessible and comes in big quantities. The production of palm oil generates a large amount of POME waste, which is then treated by anaerobic digestion to produce POME anaerobic sludge.

TABLE 2. CURRENT POME TREATMENT RESEARCH TRENDS IN MALAYSIA

Bacteria species	Method approaches	References
Parabacteroides, Bellilinea, Levilinea, Smithella and *Prolixibacter* (in POME) *Nitriliruptor, Delftia, Filomicrobium, Steroidobacter* and *Ohtaekwangia* (surface compost) *Steroidobacter, Nitriliruptor, Anaeromyxobacter, Filomicrobium* and *Filomicrobium* (inside compost) *Devosia yakushimensis* and *Desemzia incerta* (thermophilic stage), *Planococcus rifietoensis* (co-composting)	Mechanical rotary drum reactor, POME anaerobic sludge	Sabiani and Awang (2022)
Bacillus velezensis *Pseudomonas aeruginosa* (strain IASST201) *Achromobacter xylosoxidans* *Streptomyces* sp. *Gansen* and *Cellulomonas* sp. *Okoh*	Bioflocculant	Hassimi *et al.* (2020)
Bacillus subtillis and *Methanosarcinales* and *Methanobacteriales*	Bio-augmentation	Chin *et al.* (2020)

POME is an excellent microbial seed for composting since it is thicker anaerobic sludge. The study found that knowing the functions of different microorganisms, like bacteria and fungus in EFB-POME compost is essential for evaluating the efficacy of composting and producing high-quality compost (Sabiani and Awang, 2022). It demonstrates that treating POME wastewater with bacteria alone would not be effective. Nonetheless, attempts have been made to mix and combine various methods and species. From here, progress in the course of treatment can be shown (*Table 3*).

In their review, Sabiani and Awang (2022) stated that the ideal and suggested pH value for the finished compost is the decline of the pH profile. After 111 days, the carbon/nitrogen (C/N) ratio was 10.29, indicating that the compost had reached maturity and was ready to be used as an organic fertiliser in farming. Furthermore, no heavy metal elements were found, indicating that the compost was of excellent quality. This state is highly useful for tracking the maturity of the compost and the advancement of co-composting since it illustrates how the bacterial population shifts throughout the process, influencing physicochemical parameters like moisture content, temperature, and oxygen concentration.

In contrast, extracellular biopolymers secreted by microorganisms: Fungi, algae, yeast, and bacteria are known as bioflocculants. Specific media are used as feedstocks for fermentation in most bioflocculant production processes. An effective feedstock for the production of bioflocculants could be high-nutrient palm oil mill effluent (POME) (Hassimi *et al.*, 2020).

Additionally, it was noted that the bioflocculants' hydroxyl and carboxyl groups constitute important chemical functional groups for flocculation since they strongly bind to particles and other chemical contaminants. Furthermore, the bioflocculants generated in POME demonstrated a robust stretching vibration in contrast to those derived from sago mill effluent (SME) and synthetic media, which demonstrated the least amount of stretching. A study revealed that xylose and deoxy-rhamnose sugar were present in the bioflocculant made by *P. aeruginosa* (strain IASST201). A bioflocculant that was partially purified and generated from a strain of *A. xylosoxidans* revealed the presence of either glucose or galactose at 160.84 m/z. Additionally, the study discovered a range of distributions in the molecular weights of the chemicals in a bioflocculant made by *Streptomyces* sp. *Gansen* and *Cellulomonas* sp. *Okoh* grown in synthetic medium using mass spectrometry analysis (Hassimi *et al.*, 2020).

The employment of particular microorganisms to increase the desired microbial population while also speeding up the breakdown process and producing more methane is known as bio-augmentation. To help break down empty fruit bunch (EFB) and POME, mixed methanogens and *B. subtilis* were employed. *Methanosarcinales* proliferate in garbage by catabolising methyl molecules or converting acetate to methane and carbon dioxide. However, methanobacterial organisms convert hydrogen and carbon dioxide into methane gas (Chin *et al.*, 2020).

Taking into account the study by Nuid *et al.* (2023), the use of bio-augmentation synergistic with biogranulation using a lab-scale sequencing batch reactor (SBR) system under alternating anaerobic and aerobic conditions, there is excellent settleability with improved treatment efficiency after 60 days of being bioaugmented with the *Serratia marcescens SA30* strain and the flocculent biomass transformed into biogranules. This finding showed that the proposed technique can enhance the biodegradation of oil and grease (O&G) and is capable of treating real AD-POME in the future (Nuid *et al.*, 2023).

TABLE 3. RESULTS FROM BACTERIA TREATMENT AND METHOD APPROACHES

Bacteria species	Method approaches	Results	References
Parabacteroides, Bellilinea, Levilinea, Smithella, and *Prolixibacter* *Nitriliruptor, Delftia, Filomicrobium, Steroidobacter,* and *Ohtaekwangia* *Steroidobacter, Nitriliruptor, Anaeromyxobacter, Filomicrobium*, and *Filomicrobium* *Devosia yakushimensis* and *Desemzia incerta, Planococcus rifietoensis*	Mechanical rotary drum reactor, POME anaerobic sludge	pH profile decline to 7.59, the C/N ratio was 10.29, extremely low amounts of heavy metals, changes in physicochemical properties	Sabiani and Awang (2022)
Bacillus velezensis *Pseudomonas aeruginosa* (strain IASST201) *Achromobacter xylosoxidans* *Streptomyces* sp. *Gansen and Cellulomonas* sp. *Okoh*	Bioflocculant	Bioflocculant yield (2.03 g/L) at a temperature of 40°C	Hassimi *et al.* (2020)
Bacillus subtillis and *Methanosarcinales* and *Methanobacteriales*	Bio-augmentation	75% reduction in methane production	Chin *et al.* (2020)

In short, the relationship between the bacteria research trends and POME wastewater treatment is that the bacteria have improved the quality of waste significantly after the treatment. This can be confirmed with the comparison results between before and after treatment, in particular the pH profile of wastewater, the C/N ratio obtained, extremely low amounts of heavy metals left from waste, changes in physicochemical properties, and a 75% reduction in methane production (carcinogenic compounds). At the same time, the treatment can also produce beneficial products such as bio-flocculant.

- *RQ3. How is the influence of these research trends towards POME wastewater treatment in Malaysia?*

The mixture culture of bacteria species for POME wastewater treatment has been identified together with method approaches. From these findings, we can predict how the treatment works and how effectively the bacteria have been utilised in wastewater treatment. The POME anaerobic sludge's COD concentrations, total solids, volatile solids, and water content were 57.77%, 8.43%, 68.30% and 91.50% mg/L, respectively. Thickened POME anaerobic sludge is an ideal microbial seed for the composting process since it is high in nutrients, including potassium (6.5%), phosphorus (1.3%), and nitrogen (4.7%), as well as native microorganisms. When thickened POME sludge is applied during the composting process, the amount of compost produced can be increased while the composting period is shortened. Some of these bacteria used the waste as their nutrient and energy sources, and on the other side, the bacteria converted their foods into something beneficial to humans, for example, gas, fuel, and many others (Sabiani and Awang, 2022).

Since POME includes a lot of cellulose (Bakar *et al*., 2020), adding cellulolytic *B. subtilis* will help to produce the enzyme cellulase, which can break down cellulose into simpler sugars. In contrast, a class of bacteria known as methanogens uses acetate as a food source and uses anaerobic environments to create carbon dioxide and methane. Consequently, including methanogen species into the substrates will quicken the rate and production of methane gas (Chin *et al.,* 2020).

With the economy fluctuating globally nowadays, it is important to see the cost of operating, procedures for operation, and efficient methods applied to the whole treatment process. This will influence the decision to use which research trends to treat the waste.

However, it is reported that methanogenesis reactions in POME can produce approximately more than 0.8 L of biogas per gram with methane concentrations above 50%. Numerous research projects have been undertaken in an effort to maximise the profitability of POME biogas generation. The economic viability of various bioreactor layouts that have been investigated to maximise biogas output is unknown. Numerous technological approaches have also been investigated to maximise the production of biogas from POME particularly those that help boost the production of biogas using co-substrates and POME pretreatment methods. A study on the techno-economics of using biogas from POME as compressed natural gas (Bio-CNG) was also conducted in Malaysia. The results indicated that the system that uses membrane separation technology for biogas purification has the shortest payback period value and is the most cost-effective as a result. These studies demonstrate the growing diversity in biogas generating technology from POME. It offers a wide range of substitute technological choices to maximise biogas output from POME and make it sustainable and economically appealing. However, there is still need for more research into these techno-economic elements due to the complexity of the problems surrounding POME processing for sustainable environmental practices and renewable energy. Just a few numbers of research on the techno-economic aspects of the aforementioned renewable energy utilisation systems have examined the use of POME for the production of biogas, which is then used to generate electricity (Sodri and Septriana, 2022).

In addition, it is reported that the potential for POME biogas collection to produce energy with an annual revenue of RM3.8 million for a palm oil mill (POM) with a production capacity of 60 t/hr and it was mentioned a number of obstacles to the biogas system's dissemination in Malaysian POMs. The most recent review of the benefits and drawbacks of POME biogas collection and utilisation, including the most recent Malaysian policies, was recently completed by Loh *et al.* (2017) and Yap *et al.* (2021). POME biohydrogen production, particularly yield from the treatment can be used as carbon source through dark fermentation process and has potential to be bioenergy and act as alternative renewable energy source (Arisht *et al.,* 2022). Although numerous articles have been written about the benefits, challenges, and opportunities of using POME-based biogas in Malaysia and assisting with the installation of biogas facilities at POMs, no paper has addressed the advantages of removing POME from the design of an integrated palm oil complex as an alternate strategy to lower the palm oil sector's GHG output. Reducing POME production in POMs actually has a lot of potential to improve the palm oil industry's sustainability and profitability. For mill owners to have options, a comparison of POME eradication and utilisation from several angles particularly those related to the economy and environment is necessary whom biogas capturing is of no importance to. One way to address the knowledge gaps in industrial symbiosis attempts in the palm oil industry is to analyse potential process integrations within the palm oil supply chain (Tan and Lim, 2019).

In a nutshell, the influence of these research trends on POME wastewater treatment in Malaysia is the result of treatment and economic growth. Discharging wastewater on public land may cause unpleasant effects on the environment as well as human well-being. However, treating the waste with suggested bacteria species together with other integrated technology might have the potential to produce the best results as the bacteria can use chemical compounds from waste as their energy and food. Taking together the resultant of wastewater after treatment with their impact on the economy, especially in Malaysia, the beneficial product, for example, methane gas, somehow has the potential to limit Malaysia's reliance on renewable resources while also having a good impact on the economy.

Limitation. Two major limitations apply to the review that this study presents. Despite having a large number of articles under review, there is a dearth of research on the subject matter published in Scopus and WoS according to keyword searches. Research on the topic is currently ongoing, and more research is necessary to gain a deeper knowledge of it. Secondly, papers from proceedings, books, conferences, theses, and dissertations are not included in the study; only articles.

CONCLUSION

Our approach to study on research trends particularly in subsequent year for treating the discharged waste is greatly influenced by the utilisation of bacteria and biological treatment, which is an intriguing technique in today's treatment research trends. How much its utilisation can improve things in a lab-scale setting for large-scale endeavours. Because it enables the bacteria to be more agentically and behaviourally engaged with the waste and treatment, our work suggests that using bacteria and biological treatment as a handy tool has a huge potential to improve treatment and performance. In this study, three articles were firmed to report on POME treatment using bacteria. The significant effect and relationship between both bacteria and POME treatment has been discussed in the manuscript. This research indicates that the benefits of treatment may be achieved by successfully integrating bacteria and biological treatment potentially on a larger scale. Though the success of such integration depends on a variety of factors, such as the treatment's perspective on the use of mixture culture, there are some limitations to the integration of bacteria and biological treatment in particular waste concentrations. Therefore, in light of this, scholars and decision-makers would want to conduct a thorough investigation of the efficacy of combining biological treatment with bacteria as a component of regular treatment of particular wastewater. This means that more research should be done by broadening the sources from which articles are obtained, for instance by focusing on a particular publisher's study, extracting information from conferences, proceedings, books and theses, as well as relating to industry policies about biological treatment. Certain biological treatments also result from straightforward strategies and interactions with various wastes, not just relying on one study.

ACKNOWLEDGEMENT

The authors would like to thank Universiti Teknologi Malaysia (UTM) for research support and opportunities given.

REFERENCES

Abdurahman, N H; Rosli, Y M and Azhari N H (2013). The performance evaluation of anaerobic methods for palm oil mill effluent (POME) treatment: A review. *International Perspectives on Water Quality Management and Pollutant Control* (Nigel, W T Q eds.). IntechOpen Limited, London. p. 87-100.

Arisht, S N; Mahmod, S S; Abdul, P M; Lutfi, A A I; Takriff, M S; Lay, C H; Silvamany, H; Sittijunda, S and Jahim, J M (2022). Enhancing biohydrogen gas production in anaerobic system via comparative chemical pre-treatment on palm oil mill effluent (POME). *J. Environ. Manag., 321*: 115892. DOI: 10.1016/j.jenvman.2022.115892.

Bakar, S N H A; Hasan, H A; Mohammad, A W; Abdullah, S R S; Ngteni, R and Yusof, K M M (2020). Performance of a laboratory-scale moving bed biofilm reactor (MBBR) and its microbial diversity in palm oil mill effluent (POME) treatment. *Process. Saf. Environ. Prot., 142*: 1-35. DOI: 10.1016/j.psep.2020.05.004.

Chin, K L; Nurliyana, M Y; H'ng, P S; Lee, C L; Go, W Z; Khoo, P S; Nazrin, R A R and Ashikin, S N (2020). Efects of bacterial bio-augmentation on the methane potential from facultative digestion of palm oil mill effluent and empty fruit bunch. *Waste Biomass Valorization. 11*: 3407-3418.

Haris, H (2006). *Treatment of palm oil mill effluent (POME) using membrane bioreactor*. BSc. thesis. College of Engineering and Technology Malaysia.

Hassimi, A H; Hafiz, R E; Muhamad, M H and Abdullah, S R S (2020). Bioflocculant production using palm oil mill and sago mill effluent as a fermentation feedstock: Characterization and mechanism of flocculation. *J. Environ. Manag., 260*: 110046.

Kristanti, R A; Hadibarata, T; Yuniarto, A and Muslim, A (2021). Palm oil industries in Malaysia and possible treatment technologies for palm oil mill effluent: A review. *J. Environ. Res. Eng. Manag., 77(3)*: 50-65. DOI: 10.5755/j01.erem.77.3.29522.

Loh S K; Nasrin A B; Mohamad Azri S; Nurul Adela B; Muzzammil N; Daryl Jay T; Stasha Eleanor R A; Lim W S; Choo Y M and Kaltschmitt M (2017). First report on Malaysia's experiences and development in biogas capture and utilization from palm oil mill effluent under the Economic Transformation Programme: Current and future perspectives. *Renew. Sustain. Energy Rev., 74*: 1257-1274.

Madaki, Y S and Seng, L (2013). Palm oil mill effluent (POME) from Malaysia palm oil mills: Waste or resource. *Int. J. Sci. Environ. Technol., 2*: 1138-1155.

Mohammad, S; Baidurah, S; Kobayashi, T; Ismail, N and Leh, C P (2021). Palm oil mill effluent treatment processes - A review. *Processes, 9*: 739. DOI: 10.3390/pr9050739.

Moher, D; Liberati, A; Tetzlaff, J and Altman, D G (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *J. Clin. Epidemiol., 62*: 1006-1012.

MPOB (2016). http://bepi.mpob.gov.my/index.php/en/statistics/production/168-production2016/746-production-of-crude-oil-palm-2016.html., accessed on 10 November 2023.

Nuid, M; Aris, A; Abdullah, S; Fulazzaky, M A and Muda, K (2023). Bioaugmentation and enhanced formation of biogranules for degradation of oil and grease: Start-up, kinetic and mass transfer studies. *J. Environ. Manag., 341*: 118032. DOI: 10.1016/j.jenvman.2023.118032.

Palm Oil Analytics (2024). Malaysia's 2023 CPO production up 0.5% y-o-y at 18.55 mil mt: MPOB. https://www.palmoilanalytics.com/malaysias-2023-cpo-production-up-0-5-y-o-y-at-18-55-mil-mt-mpob/#:~:text=News-,Malaysia's%202023%20CPO%20production%20up%200.5%25%20y%2Do%2Dy%20at%2018.55%20mil,Palm%20Oil%20Board%20(MPOB), accessed on 17 February 2024.

Sabiani, N H M and Awang, N (2022). Aerobic composting of oil palm fronds - A review. *Appl. Ecol. Environ. Res., 20*: 2509-2533.

Sodri, A and Septriana, F E (2022). Biogas power generation from palm oil mill effluent (POME): Techno-economic and environmental impact evaluation. *Energies, 15*: 7265. DOI: 10.3390/en15197265.

Soo, P L; Bashir, M J K and Wong, L P (2022). Recent advancements in the treatment of palm oil mill effluent (POME) using anaerobic biofilm reactors: Challenges and future perspectives. *J. Environ. Manag., 320*: 115750. DOI: 10.1016/j.jenvman.2022.115750.

Tan, Y D and Lim, J S (2019). Feasibility of palm oil mill effluent elimination towards sustainable Malaysian palm oil industry. *Renew. Sustain. Energy Rev., 111*: 507-522.

Vijayaraghavan, K; Ahmad, D and Aziz, M E A (2007). Aerobic treatment of palm oil mill effluent. *J. Environ. Manag., 82(1):* 24-31. DOI: 10.1016/j.jenvman.2005.11.016.

Wu, T. Y; Mohammad, A. W; Jahim, J and Anuar, N (2009). A holistic approach to managing palm oil mill effluent (POME): Biotechnological advances in the sustainable reuse of POME. *Biotechnol. Adv., 27*: 40-52.

Yap, C C; Loh, S K; Chan, Y J; Supramaniam, C V; Chong, M F; Soh, A S; Lim, L K and Loo, L S (2021). Synergistic effect of anaerobic co-digestion of palm oil mill effluent (POME) with *Moringa oleifera* extract. *Biomass Bioenergy, 144*: 105885. DOI: 10.1016/j.biombioe.2020.105885.

Zainal, N H; Jalani, N F; Mamat, R and Astimar, A A (2017). A review on the development of palm oil mill effluent (POME) final discharge polishing treatments. *J. Oil Palm Res., 29(4)*: 528-540.