

# EMERGING POLLUTION CONTROL TECHNOLOGIES FOR THE TREATMENT OF PALM OIL MILL EFFLUENT (POME) THROUGH MICROBIAL BIODEGRADATION USING FUNGI: CHALLENGES AND FUTURE PERSPECTIVES

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## ABSTRACT

*Palm oil mill effluent (POME) is a high-strength wastewater which is rich in nutrients, organic matter and suspended solids. Discharging POME without adequate treatment into the environment can cause undesirable hazards to both humans and the environment. Conventional treatment methods, such as ponding systems and anaerobic digestion, are widely applied but face several limitations in managing POME, including inconsistent removal efficiency, extended treatment duration, extensive land use and unfavourable weather conditions. In contrast, fungal-based treatment systems are gaining interest due to the ability of the fungi to produce a wide range of extracellular enzymes, degrade complex organic or recalcitrant pollutants and possess remarkable adaptability to harsh environmental conditions. This review highlights the advantages of the fungal-based treatment systems over conventional treatment methods. It also focuses on the potential of diverse fungal strains as emerging pollution control for POME treatment, as well as in understanding fungal pollutant removal mechanisms and operational factors that influence fungal-based treatment performance. Finally, the review identifies the implementation challenges and future research directions, providing a comprehensive perspective on fungal-based POME treatment as a sustainable and scalable technology for pollution control.*

**Keywords:** biodegradation, emerging technologies, enzyme, fungal-based treatment, palm oil mill effluent.

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## INTRODUCTION

Malaysia and Indonesia are recognised as the main palm oil producers in the world, supplying nearly 85.0% of the global palm oil production

(Kristanti et al., 2021), followed by Thailand, which contributes 4.0% of the global palm oil production (Iskandar et al., 2018). This extensive amount of palm oil production meets rising worldwide demand, representing around 33.0% of the global fats and oils (Tan & Lim, 2019). The palm oil industry also contributes to the global economy due to its extensive application in different sectors, such as biofuels, agrifood and personal care products. While the palm oil industry has been a key driver of economic growth, its rapid development has also contributed to large-scale deforestation and habitat loss, which has increased greenhouse gas (GHG) emissions and freshwater source pollution.

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From 2000 to 2020, the global oil palm plantations expanded by more than 18 million hectares, primarily in Southeast Asia (Yu et al., 2024). This expansion required extensive deforestation, accounting for approximately 1.4% of the global net carbon emissions. A significant contributor to this environmental challenge lies in the handling of POME, a high-strength wastewater produced during the palm oil extraction process (Khatiwada et al., 2021; Meijaard et al., 2020; Ratnasari et al., 2022). The production of every tonne of crude palm oil yields up to 3.75 t of POME, which can cause severe water pollution if not adequately treated (Arisht et al., 2020). The palm oil industry has responded to this problem by commonly implementing conventional treatment systems (Pauzi et al., 2023). However, these systems are associated with several limitations, including inconsistent removal efficiency, extended retention times, extensive land use and unfavourable weather conditions.

In response to environmental concerns, numerous approaches have recently been conducted on various methods to address the limitations of conventional treatment systems. Among other treatment methods, fungal-based treatment has gained significant recognition as a valuable approach in POME management due to its remarkable biodegradation capabilities (Akerman & Rojas, 2021; Latif et al., 2023; Legorreta et al., 2020; Marycz et al., 2022; Tamjidi et al., 2023). The application of fungi is an effective solution for treating diverse wastewater types due to their unique metabolic and enzymatic abilities, which allow them to produce extracellular enzymes that efficiently degrade complex organic pollutants (Ghosh et al., 2023; Naeem et al., 2022; Singh et al., 2021). Additionally, fungi exhibit an exceptional versatility in utilising different substrates, enabling the degradation of various recalcitrant pollutants (Aiduang et al., 2022; Langton et al., 2022). Fungi also possess a remarkable adaptability to harsh environmental conditions (Branco et al., 2022; Krah et al., 2022). These superior resistances and adaptations enable them to thrive in extreme environments compared to other microorganisms (Priyadarshini et al., 2021; Rahman, 2020).

Despite growing interest in fungal-based POME treatment, significant gaps remain in systematically evaluating the performance of diverse fungal strains. There is also a limited understanding of fungal pollutant removal mechanisms and operational factors that influence fungal activity. To address these gaps, this review has three key objectives: (i) To systematically assess the potential and pollutant removal efficiency of various fungal strains in POME treatment, (ii) to understand the pollutant removal mechanism using fungal-

based POME treatment, and (iii) to evaluate the implementation challenges, scalability, and future opportunities for fungal-based POME treatment. Therefore, by clarifying the objectives of this study, this review presents a focused framework for using fungi as a sustainable alternative to conventional POME treatment.

## CHARACTERISTICS OF PALM OIL MILL EFFLUENT

POME is a viscous and brownish liquid containing approximately more than 95.0% water, 2.0%–4.0% fine cellulose debris, and 0.6%–0.7% oils (Azmi & Yunos, 2014; Mohammed & Chong, 2014). It also exhibits high concentrations of total suspended solids (TSS), acidity, oil and grease (O&G), biological oxygen demand (BOD), chemical oxygen demand (COD), ammoniacal nitrogen ( $\text{NH}_3\text{-N}$ ), and total nitrogen (TN). The pH of raw POME typically ranges between 3.4 and 5.2, while its temperature can reach up to 90°C. Consequently, discharging POME into natural waterways without proper treatment severely impacts the aquatic ecosystem by reducing water transparency and inhibiting photosynthesis, leading to oxygen depletion, eutrophication and the contamination of freshwater sources, while also posing serious human health risks like irritation, poisoning, genetic mutations and cancer. Therefore, to mitigate these environmental risks, regulatory authorities have established effluent discharge standards for POME.

In Malaysia, the Department of Environment (DOE) enforces these standards in accordance with the Environmental Quality (Prescribed Premises Crude Palm Oil) Regulations 1977 under the Environmental Quality Act (EQA) 1974. Specifically, these standards set the maximum allowable concentrations for parameters like COD, BOD, TSS,  $\text{NH}_3\text{-N}$ , O&G and TN that must be met before treated effluent can be discharged into natural waterways. Comparable regulatory frameworks also exist globally among other palm oil producing countries. Indonesia, the largest producer of palm oil in the world, enforces effluent standards under the Regulation of the Ministry of Environment of the Republic of Indonesia No. 5/2014, which also sets the maximum limits for pollutants like BOD, COD, TSS, oil and fat (O&F) and TN (Putra et al., 2024). The general characteristics of raw POME, the average value of raw POME and its respective standard discharge limit set by Malaysia and Indonesia are shown in *Table 1*.

Moving beyond the national regulations, the Roundtable on Sustainable Palm Oil (RSPO) was established in 2004 to promote the sustainable production of palm oil through the

development of global standards and stakeholder engagement (Iskandar et al., 2018). It is a set of strict environmental and social criteria that requires mill companies to meet specific effluent treatment benchmarks to get RSPO certification, encouraging sustainable wastewater management. This also aligns with the international environmental standards, which not only mitigate the ecological footprint of POME but also directly influence market competitiveness, as global buyers increasingly demand for RSPO certification (Dermoredjo et al., 2025). Even without local palm oil production, the European Union (EU) uses indirect influence on exporting countries through stringent environmental directives such as the Water Framework Directive (2000/60/EC) and the Industrial Emissions Directive (2010/75/EU) (Brandstätter et al., 2025).

Thus, by considering POME management within the national and international regulations, it emphasises the critical demand for more innovative, efficient, and sustainable POME treatment strategies. Since conventional methods often struggle to achieve these essential goals, these limitations highlight the growing relevance of alternative treatments, particularly fungal-based treatments.

## CONVENTIONAL POME TREATMENTS

### Ponding Systems

Conventional POME treatment approaches, such as ponding systems and anaerobic digestion, demonstrate the ability to reduce organic pollutants while maintaining cost-effectiveness (Lok et al., 2020). Ponding systems rely on the natural decomposition process for reducing organic pollutants, offering a reasonable degree

of treatment capabilities at minimal energy consumption, low initial investment and limited technical expertise requirements. These features make ponding systems an attractive option for mills operating in resource-limited settings.

Despite these benefits, ponding systems are progressively being considered outdated and unsustainable for modern industrial requirements (Kim, 2021). The pollutant removal efficiency remains a significant limitation. BOD removal can reach 90% under ideal conditions, while COD reduction usually ranges between 50%–70% (Jumadi et al., 2020; Lokman et al., 2021; Yunus et al., 2015). Additionally, oil and grease removal is inconsistent, frequently failing to meet stringent discharge standards. Moreover, they necessitate extensive land use, occasionally exceeding 1–2 ha per mill, depending on the production capacity. Between 2000 and 2020, the global area of oil palm plantations expanded at an average of 0.92 million hectares per year (Soo et al., 2022; Yu et al., 2024). The treatment durations can also be as long as 60–90 days before effluent discharge (Mohammad et al., 2021; Sabiani et al., 2023). Unfortunately, extended retention times can lead to the production of greenhouse gases that substantially contribute to climate change. These limitations highlight the critical need for an environmental sustainability alternative or complementary treatment strategies that can achieve higher efficiency.

### Anaerobic Digestion

Anaerobic digestion in digester tanks has been recommended as a better alternative to the ponding systems. Compared with the ponding systems, this method is preferable as it produces more stable effluent discharge, effectively reduces pollutants and simultaneously generates biogas, which can

TABLE 1. TYPICAL CHARACTERISTICS FOR POME AND ITS DISCHARGE LIMIT IN MALAYSIA AND INDONESIA

Parameters <sup>a</sup>	Concentration range of POME <sup>b</sup>	Average value of raw POME <sup>c</sup>	Malaysia discharge limits <sup>d</sup>	Indonesia discharge limits <sup>e</sup>
COD	15,000–100,000	51,000	1,000	350
BOD	10,250–43,750	25,000	100	100
TSS	5,000–54,000	18,000	400	250
NH <sub>3</sub> -N	4–80	35	150	-
O&G	130–18,000	6,000	50	-
O&F	-	-	-	25
TN	180–1,400	750	200	50
Temperature	80°C–90°C	24.8°C	45°C	-
pH	3.0–5.2	4.2	5.0–9.0	6.0–9.0

Note: COD - chemical oxygen demand; BOD - biological oxygen demand; TSS - total suspended solids; NH<sub>3</sub>-N - ammoniacal nitrogen; O&G - oil and grease; TN - total nitrogen; POME - palm oil mill effluent. <sup>a</sup> - All values, except pH and temperature, were expressed in mg/L; <sup>b</sup> Rajani et al. (2019); <sup>c</sup> Kamyab et al. (2018); <sup>d</sup> - Environmental Quality (Prescribed Premises Crude Palm Oil) Regulations 1977; <sup>e</sup> - Regulation of the Minister of Environment of the Republic of Indonesia No. 5/2014

be used as a renewable energy source (Chan et al., 2012; Yunus et al., 2015). Anaerobic digestion is also widely considered to be an environmentally friendly and cost-effective method (Chin et al., 2013; Soo et al., 2022).

Despite its advantages, anaerobic digestion exhibits several key inefficiencies in POME treatment. The process typically achieves 80%–95% BOD removal but only 50%–70% COD removal, which is insufficient to meet regulatory discharge limits that often require over 90% of removal efficiency (Ramón et al., 2024). Similarly, O&G removal is frequently inconsistent, with residual concentrations that necessitate additional treatment to meet the permissible limit of < 50 mg/L (Muhammad et al., 2023; Soo et al., 2022). The hydraulic retention time (HRT) is also relatively long, with a typical treatment time of 20–30 days, which restricts throughput and increases land requirements (Lokman et al., 2021; Murti et al., 2024; Zainal et al., 2022). Cumulatively, these limitations demonstrate that although anaerobic digestion is relatively better than ponding systems, it cannot consistently achieve the high pollutant removal efficiency or short treatment durations. This highlights the need to integrate existing treatment with complementary treatment processes, including alternative or additional steps such as fungal-based systems, to meet compliance standards and enhance environmental sustainability.

#### POLLUTANT REMOVAL MECHANISM USING FUNGAL-BASED TREATMENT

The pollutant removal mechanism using fungal-based treatment involves a combination of biosorption, enzymatic biodegradation and intracellular metabolism that convert or transform complex pollutants into more manageable substances and less harmful products. These mechanisms are fundamental to the overall effectiveness of POME treatment using fungi, as they integrate physical adsorption and biochemical conversion within the fungal system. Figure 1 illustrates these mechanisms, showing

the adsorption of pollutants onto the fungal cell, extracellular degradation and subsequent intracellular degradation.

Biosorption represents the initial phase of fungal pollutant removal, where fungi act as efficient biosorbents due to their cell wall are highly composed of polysaccharides and proteins. These cell wall components also comprise a large variety of functional groups such as carboxyl, hydroxyl, amine and phosphate. Functionally, these groups facilitate fungal interactions with pollutants through mechanisms such as ion exchange, electrostatic interaction, microprecipitation and complex formation (Sadhasivam et al., 2009). Fungal species such as *Aspergillus niger*, *Penicillium chrysogenum* and *Rhizopus arrhizus* have demonstrated strong biosorption capacities in wastewater treatment, effectively adsorbing and removing diverse organic and inorganic pollutants (Mohammed et al., 2024). For organic pollutants, biosorption helps concentrate the compounds near the fungal hyphae, which allows extracellular enzymes to access and degrade them more effectively. In the case of inorganic pollutants, including heavy metals such as lead, cadmium, copper, chromium and nickel, biosorption occurs via either surface attachment or intracellular accumulation, in which metal ions are immobilised or stored within fungal cells. Overall, this adsorption process acts as an essential preliminary step that enhances subsequent enzymatic degradation and supports the overall pollutant removal process.

After biosorption, extracellular enzymatic degradation becomes a key mechanism for pollutant removal using fungal-based treatment, breaking large molecules into smaller intermediates. The interaction begins with substrate recognition and attachment between fungi and pollutants, in which hyphal structures serve as dynamic explorers, allowing physical contact with pollutant surfaces and initiating the degradation process (El-Gendi et al., 2021; Steffan et al., 2020). This stage not only serves as a passive physical process but also allows fungi to anchor onto substrate surfaces, facilitating the release of enzymes directly onto the substrates. The continuous growth of hyphae

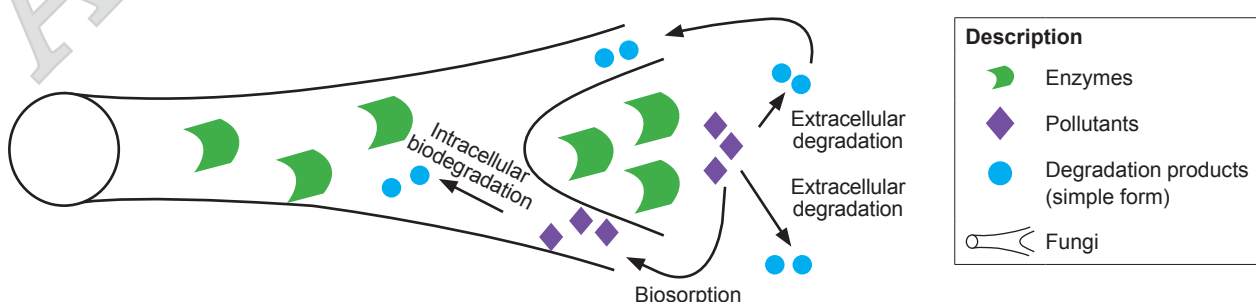


Figure 1. Schematic diagram of pollutant removal mechanism using fungi.

further increases the surface area in contact with the pollutants and creates a stable environment that enhances the overall efficiency of the degradation process (Steffan et al., 2020). Once the attachment occurs, the fungi persistently secrete a diverse set of extracellular enzymes directly onto the pollutants, maximising the degradation efficiency and this ongoing enzymatic activity enables fungi to effectively degrade various types of pollutants, ranging from complex organic matter to more recalcitrant substances (Marycz et al., 2022; Okal et al., 2023).

From a taxonomic perspective, fungi are primarily classified as Ascomycota, Basidiomycota and Zygomycota. Members of the Ascomycota, such as *Aspergillus* sp. and *Penicillium* sp., are characterised by their ability to produce hydrolytic enzymes, including cellulases, hemicellulases and lipases, which degrade cellulose, hemicellulose and triglycerides (Wong et al., 2021). Basidiomycota, such as *Phanerochaete chrysosporium* and *Trametes versicolor*, are efficient lignin degraders that secrete ligninolytic enzymes, including laccases (Lac), lignin peroxidases (LiP) and manganese peroxidases (MnP), which can break down phenolics and aromatic compounds (Tauro et al., 2021). Zygomycota, represented by genera such as *Rhizopus* and *Mucor*, play a key role in lipid and protein degradation through the activity of lipases and proteases, facilitating the hydrolysis of fats and nitrogenous compounds (Pfundler et al., 2019).

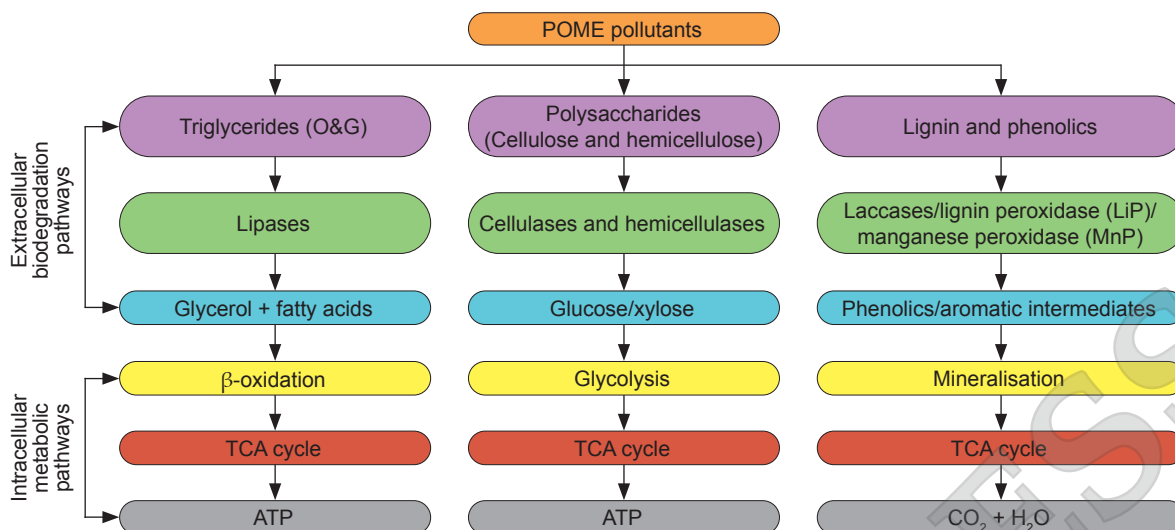
Beyond this extracellular stage, the metabolic process inside fungal cells also represents a fundamental part of the pollutant removal mechanism in the fungal-based treatment. Once the pollutants are converted into smaller or more bioavailable substrates, these products are taken up by the fungal cell for further metabolism through intracellular pathways (Fenner et al., 2021; Orhan, 2024). For instance, species like *Aspergillus* sp. and *Penicillium* sp. produce a complete suite of cellulases, comprising endoglucanases, cellobiohydrolases and  $\beta$ -glucosidases, which act synergistically to drive the hydrolysis of cellulose into glucose monomers (Panchapakesan & Shankar, 2016). These cellulase systems perform specific functions, such as endoglucanases initiate internal cleavage of cellulose chains, cellobiohydrolases release cellobiose units from the chain ends and  $\beta$ -glucosidases hydrolyse these disaccharides into glucose monomers (Baldrian & Valášková, 2008). The resulting glucose is absorbed into the fungal cells and metabolised through glycolysis to form pyruvate, which is subsequently converted to acetyl-CoA. Then acetyl-CoA enters the tricarboxylic acid (TCA) cycle and oxidative phosphorylation, generating adenosine triphosphate (ATP) as the primary energy source. Similarly, lipases catalyse the hydrolysis of triglycerides into glycerol and fatty acids. The

glycerol is metabolised through the glycolytic pathway, while fatty acids are transported into mitochondria and undergo  $\beta$ -oxidation, yielding successive two-carbon acetyl-CoA units that feed into the TCA cycle (Gupta & Gupta, 2021). This integrated metabolism provides energy in the form of ATP, sustaining fungal growth and enzymatic activity during pollutant degradation process.

Besides, white-rot fungi, such as *P. chrysosporium* and *T. versicolor*, produce a suite of ligninolytic enzymes (Lac, LiP and MnP) that catalyse the oxidative reactions to degrade recalcitrant organic compounds like lignin, phenolics and synthetic dyes (Konan et al., 2024; Mohammed et al., 2024). Lac oxidises phenolic compounds and, with the help of small-molecule mediators, can also oxidise non-phenolic compounds, generating highly reactive free radicals. LiP is a high redox potential enzyme, which is crucial for oxidising both phenolic and nonphenolic structures through mechanisms such as demethoxylation, hydroxylation and aromatic ring cleavage, while MnP catalyses the oxidation of  $Mn^{2+}$  to  $Mn^{3+}$ , which forms a chelated complex acting as a powerful diffusible redox mediator capable of attacking complex organic molecules. Collectively, these enzymes initiate the non-specific, free-radical-mediated depolymerisation of large, insoluble polymers outside the cell, breaking them down into smaller, soluble aromatic and aliphatic fragments. These degradation products are subsequently absorbed by the fungal hyphae, where intracellular metabolic pathways further process them through sequential catabolic reactions, ultimately leading to complete mineralisation into carbon dioxide and water. Figure 2 summarises these sequential pathways, illustrating the conversion of complex pollutants in POME into simpler compounds through extracellular biodegradation and subsequent intracellular metabolic pathways.

## FACTORS AFFECTING THE FUNGAL TREATMENT

The effectiveness of POME treatment using fungi is directly influenced by various factors, including temperature, pH level, HRT, aeration or agitation method, nutrient availability, fungal strain selection, organic load and pollutant concentration, which play a pivotal role in creating a conducive environment for fungal biodegradation, promoting optimal fungi growth and activity (Ali et al., 2017; Mannaa & Kim, 2017; Mustafa et al., 2023; Reihani & Khosravi-Darani, 2019; Umar et al., 2023). Therefore, understanding these variables is crucial to ensuring the fungi perform at their maximum potential, reducing the pollutants in POME efficiently.



Note: TCA - tricarboxylic acid; ATP - adenosine triphosphate.

Figure 2. Extracellular degradation pathway and intracellular metabolic pathway.

### Temperature

Temperature is one of the most pivotal operational factors influencing the growth and activity of fungi. Different fungal species have preferred temperature ranges in which they can thrive and perform efficiently in the biodegradation process. For instance, species such as *A. niger*, *Trichoderma harzianum*, *Emericella nidulans* and *Meyerozyma guilliermondii* generally perform well at moderate temperatures ranging from 25°C to 35°C (Ganapathy et al., 2019; Suseela & Muralidhar, 2018) while *Rhizopus oryzae* thrives at a higher temperature around 45°C (Prasertsan & Binmaeil, 2018). These preferred temperatures are closely tied to the metabolic activities and enzyme production capabilities of the fungi (Michele et al., 2022; Suttinun et al., 2025). When environmental temperatures align with optimal ranges, fungi can grow robustly and secrete extracellular enzymes at maximum levels, resulting in more efficient degradation of organic pollutants in POME. However, deviations from the preferred temperature can significantly impact the performance of the fungi. Conversely, deviations from a lower temperature can slow down enzyme activity, metabolic rates and fungal growth, while excessively high temperatures potentially denature enzymes and inhibit fungal growth (Showkat et al., 2024).

### pH Level

The pH level plays an important role in the treatment process as it significantly impacts both the growth of fungi and the activity of enzymes involved in pollutant degradation (Michele et al., 2022). Fungi are highly sensitive to pH variations,

which can influence their metabolic activities, cell wall stability, and the efficiency of enzyme secretion. Optimum pH values typically range between 4.0 and 8.0 for most fungal species. Within this range, fungi like *M. guilliermondii* and *R. oryzae* exhibit maximum enzymatic activity (Ganapathy et al., 2019; Prasertsan & Binmaeil, 2018; Ridtibud et al., 2024). However, if the pH falls outside this optimal range, the enzymatic breakdown of pollutants can become inefficient. For instance, extremely alkaline condition could reduce the solubility of organic pollutants, making them less accessible for breakdown, whereas extremely acidic conditions can denature enzymes or damage fungal cell membranes. Thus, maintaining a stable and suitable pH level is critical for maximising the effectiveness of fungal-based POME treatment systems.

### Hydraulic Retention Time (HRT)

Fungal growth, enzymatic activity, and the overall effectiveness of pollutant degradation are all strongly impacted by HRT, which is an essential operational condition in fungal-based POME treatment systems. HRT refers to the period that wastewater remains in the system, giving fungi enough contact and metabolic processing time to break down complex pollutants. Optimal HRT facilitates fungal colonisation, hyphal extension and the secretion of extracellular enzymes, ensuring effective degradation of organic matter. Based on the previous studies, optimal HRT ranging from 3 to 10 days enables fungi such as *A. niger* and *T. hirsuta* AK04 to achieve high pollutant removal (Kietkwanboot et al., 2022; Ridtibud et al., 2024; Thegarathah et al., 2022). Excessively long HRT can result in inefficiency, including decreased throughput, overgrowth and

higher operational costs. However, shorter HRT might hinder fungal adaptation to metabolise the pollutants, resulting in ineffective pollutant removal (Beltrán-Flores et al., 2024; Kawan et al., 2022; Mofijur et al., 2023). Striking a balance between efficiency and operational capacity necessitates constant monitoring and dynamic modifications to HRT, making it an important parameter for optimising the performance of fungal-based treatment systems.

### Aeration and Agitation Methods

Aeration and agitation methods are important operating conditions for fungal growth, enzymatic activity and overall effectiveness in fungal-based POME treatment systems. Aerobic fungi such as *Aspergillus*, *Penicillium* and *Trichoderma* rely heavily on a consistent oxygen supply to promote optimal growth and metabolic activities, which are important for their pollutant degradation capabilities (Dominic & Baidurah, 2022; Nwuche et al., 2014). A steady oxygen flow is essential not only for supporting fungal growth and metabolism but also for enhancing the production of the enzyme and substrate degradation rates by maintaining the effects of agitation speed and aeration (Razak et al., 2022). Additionally, it facilitates the even distribution of nutrients, oxygen and pollutants, ensuring consistent interaction between fungi and substrates while preventing the accumulation or settling of solids and biomass. In large-scale operations, inadequate aeration can result in oxygen depletion, which can impede fungal development and reduce overall treatment efficiency. In contrast, anaerobic fungi such as *Neocallimastix*, *Piromyces* and *Orpinomyces* thrive under anoxic conditions and exhibit strong metabolic potential for degrading lignocellulosic substrates (Bhagat et al., 2023; Dehghani et al., 2020; Ramasamy, 2024). Despite these capabilities, their application in large-scale POME treatment is currently underutilised. Therefore, exploring their cultivation strategies, metabolic pathways optimisation, and synergistic interactions with other microorganisms are crucial steps toward maximising their potential for more sustainable POME management.

### Nutrient Availability

Nutrient availability is an important aspect that determines the efficiency of fungal-based POME treatment systems, since nutrients are required for fungal growth, metabolism and enzymatic activity. While POME is rich in organic carbon, it often lacks essential nutrients, particularly nitrogen and phosphorus, which are crucial for sustaining fungal growth, enzyme production and pollutant degradation (Osman et al., 2020). To address this,

nutrient supplementation might be necessary in some cases to maintain optimal conditions. However, excessive nutrient supplementation can also result in toxicity, emphasising the importance of proper nutrition control. By providing adequate food availability, fungi can grow vigorously, release enzymes effectively and break down pollutants efficiently, thus contribute to an improved treatment performance with shortened processing time.

### Organic Load and Pollutant Concentration

Organic load and pollutant concentration are also important factors that influence the effectiveness of fungal-based POME treatment systems. High levels of organic loads in POME provide an abundance of substrates for fungal metabolism. However, excessive organic loads can significantly reduce the efficiency of fungal-based treatment, leading to a slower rate of pollutant degradation (Gikas et al., 2022; Malik et al., 2023; Zhang et al., 2018). High organic loads often require prolonged HRT or sequential treatment processes for efficient pollutant degradation. Shock loads or sudden increases in pollutant volume, can also overwhelm the biological treatment capacity of the systems. This leads to reduced efficiency, stressed or inhibited microbial activity and even system failure. Conversely, if the organic load is too low, fungal growth and enzyme production may be insufficient due to substrate limitation, resulting in poor pollutant removal efficiency.

### Fungal Strain Selection

The selection of fungal species or strains is one of the most critical factors impacting the efficiency of POME treatment. Each fungal species has unique physiological characteristics, metabolic capabilities and enzymatic activities that directly influence the nature of its degradation products and biodegradation process. Different fungal species exhibit considerable variability in growth rates, oxygen requirements, enzyme secretion profiles, tolerance to extreme conditions and inhibitory compounds present in effluent streams. For instance, white-rot fungi such as *P. chrysosporium* are well known for producing a broad spectrum of ligninolytic enzymes, but their activity is highly sensitive to environmental fluctuations (Konan et al., 2024). In contrast, fast-growing species such as *Aspergillus* and *Trichoderma* are more adaptable because they can utilise diverse substrates and tolerate a wider range of conditions, making them ideal for challenging wastewater environments (Ravenel et al., 2024; Ren et al., 2022). *Aspergillus*, *Trichoderma* and *P. chrysosporium* are widely applied due to

their ability to synthesise powerful enzymes, including cellulases, laccases and peroxidases, which are essential for the breakdown of complex organic contaminants (Dominic & Baidurah, 2022; Šimonovičová et al., 2021; Suseela & Muralidhar, 2018; Thegarathah et al., 2024).

Equally important is the nature of the degradation products formed during fungal metabolism. Although fungal metabolism generally converts complex macromolecules into simpler compounds, some intermediates, like phenolics derivatives, organic acids or partially oxidised aromatics, can still be toxic (Khali et al., 2021; Panigrahy et al., 2022). These byproducts can pose harm to downstream water quality and necessitate additional polishing steps to achieve the regulatory discharge standards. Conversely, certain degradation products, such as organic acids, biosurfactants or fermentable sugars, present opportunities for resource recovery and valorisation within a circular bioeconomy. Thus, to ensure a fungal-based POME treatment is scalable and sustainable, the selected strain must be evaluated based on its physiological characteristics, metabolic capabilities, enzymatic activities and the nature of its degradation products.

### POME TREATMENT USING FUNGI

The effectiveness of POME treatment using fungi is primarily determined by its ability to degrade pollutants, while its overall performance is strongly influenced by various operational factors. A thorough understanding of the interplay between fungal pollutant removal ability and these influencing factors is crucial for designing effective and scalable fungal-based POME treatment systems. This section reviews recent findings on pollutant removal and key influencing factors in fungal treatment of POME, highlighting both advancements and potential practical considerations for the industrial applications. Table 2 summarises the removal efficiency of POME treatment using various fungal strains. Based on the table, the efficiency of pollutant removal varies across species, with some fungi achieving over 90% of COD and BOD removal, while others demonstrate moderate efficiency but high adaptability to harsh environments. These data collectively emphasise that strain selection, operational factors and treatment configuration are critical in determining performance outcomes, highlighting the necessity of aligning fungal capabilities with specific treatment objectives.

The study reported by Suseela and Muralidhar (2018) showed that five fungal species, including *E. nidulans* NFCCI 3643, *T. reesei*, *T. harzianum*, *A. niger* and *A. fumigatus*, were isolated

from POME dump sites of Pedavegi Palm Oil Mill, West Godavari District, India. Among the fungi tested, *E. nidulans* NFCCI 3643 achieved notable removal efficiencies of 80.3% in COD, 88.2% in BOD, and 87.3% in O&G within five days under optimal environmental and nutritional conditions, demonstrating the crucial role of maintaining a suitable environment for fungal metabolism and enzymatic activity. However, utilising a consortium of microorganisms proved to be more effective compared to single microorganism cultures, as mixed cultures of *E. nidulans*, *A. niger* and *A. fumigatus* achieved 91.4% of COD and 94.3% of BOD removal under similar conditions, demonstrating superior metabolic flexibility and pollutant degradation compared to a single strain (Dominic & Baidurah, 2022; Nwuche et al., 2014; Suseela & Muralidhar, 2018). These findings emphasise that well-selected fungal strains within controlled operational conditions present significant potential for the development of an efficient and sustainable POME treatment strategy.

Thermotolerant fungi such as *R. oryzae* ST29 demonstrate significant potential in POME treatment, due to their ability to withstand high temperature and degrade complex organic pollutants. Isolated from palm oil mill environments, *R. oryzae* ST29 achieves 60.0% COD removal, 98.6% O&G removal and 52.9% total solids removal within a five-day HRT at 45°C (Prasertsan & Binmaeil, 2018). This impressive performance was linked to its high production of extracellular enzymes, including carboxymethyl cellulase and xylanase, which are the key for organic matter degradation. Process parameters, such as a 1:1 POME dilution, optimal nitrogen supplementation (0.025% urea), and an initial pH of 4.5, significantly influence fungal growth, enzyme activity and biopolymer production. Despite the presence of inhibitory phenolic compounds in POME, *R. oryzae* ST29 adapted successfully and demonstrated strong treatment capability. Collectively, these findings maximise the potential of fungal-based systems for managing POME with the valuable addition of bioproduct recovery.

The study by Ganapathy et al. (2019) demonstrated the bioremediation potential of *M. guilliermondii* degraded pollutants through enzymatic processes, significantly reducing COD by 72.0%, TN by 49.2%, NH<sub>3</sub>-N by 45.1%, TOC by 46.6%, phosphate by 60.6% and O&G by 92.4%. These results align with enzymatic degradation mechanisms, including the role of extracellular enzymes in breaking down complex pollutants and the ability of fungi to sequester or transform nutrients and toxic compounds. The improved seed germination rates in the treated effluent highlight the detoxification potential of fungal treatment, indicating reduced phytotoxicity and showcasing

the ecological relevance of fungal biodegradation. This study further emphasises the crucial role of operational factors such as nutrient availability, pH and retention time in optimising fungal-based POME treatment. Overall, these results highlight the critical role of strain selection and operational optimisation in developing sustainable and high-efficiency fungal-based POME treatment systems.

The study by Riddibud et al. (2024) further validated the central role of the fungal mechanisms in the biodegradation of persistent pollutants in POME, particularly through the enzymatic activity of the white-rot fungus *T. elegans* PP17-06. This strain demonstrated effective decolorisation performance, achieving up to 55.6% efficiency over 24 days and an optimal of 47.7% at eight-day HRT, reflecting the importance of HRT as a key factor influencing the treatment efficacy. The breakdown of these largely treatment-resistant colour compounds was linked to the activity of ligninolytic enzymes, notably manganese peroxidase, consistent with the enzyme-mediated oxidative breakdown mechanism for complex organic matter in POME. This enzymatic capability aligns with previously discussed fungal treatment pathways, where fungi secrete extracellular enzymes to mineralise lignin-like and phenolic compounds. The study further underscores the importance of nutrient availability by demonstrating that glucose and yeast extract supplementation enhanced the breakdown of phenolic compounds, thus reinforcing the critical role of optimised nutrient sources in supporting fungal metabolism and pollutant degradation.

Kietkwanboot et al. (2022) reported that the use of *T. hirsute* AK04, a white-rot fungus known for robust ligninolytic enzyme production, aligns with pollutant removal mechanisms where extracellular enzymes like manganese peroxidases are crucial for breaking down recalcitrant phenolic compounds in POME. The implementation of a temporary immersion bioreactor (TIB) with oil palm fibre (OPF) serves as an immobilisation matrix, directly influencing fungal performance through the physical configuration and process design, which encompasses aeration dynamics and hydraulic retention patterns. An immersion cycle of 6 hr submerged and 2 hr non-immersed proved optimal for dephenolisation, resulting in 85.0% phenolic compounds removal and up to 80.0% COD reduction within 168 hr, demonstrating the critical roles of HRT, oxygen availability and reactor design in boosting treatment efficiency. Beyond the pollutant removal, the process contributed to biogas enhancement during anaerobic digestion and generated nutrient-rich fungal biomass with potential as animal feed, underscoring the dual environmental and economic benefits of this approach.

The study conducted by Neoh et al. (2014) demonstrated that the effectiveness of *Curvularia clavata*, isolated from pineapple solid waste, in POME treatment, achieving 80.0% of colour removal within five days through enzymatic degradation of polyphenolic compounds and lignin. Additionally, the fungi also reduce COD by 41.0%, TOC by 53.0%, lignin by 67.0%,  $\text{NH}_3\text{-N}$  by 65.0% and phosphate by 91.0%, indicating their capacity to metabolise complex pollutants and assimilate nutrients. The effectiveness of *C. clavata* also reflects the significant impact of well-regulated conditions, such as pH, nutrient supplementation and HRT, which are highly effective in maximising fungal activity for reducing the pollutant load and toxicity of agro-industrial wastewaters like POME. These findings underscore the importance of selecting resilient fungal strains with strong enzymatic capabilities and carefully optimising operational parameters to ensure effective and comprehensive POME treatment.

The research conducted by Peace and Ome (2014) evaluated the native fungi *Geotrichum candidum* and *Candida rugosa*, sourced from local palm oil mills and tested under optimised environmental conditions, underlining the significant impact of the environmental parameters like pH, temperature, nutrient availability and inoculum size on fungal effectiveness. The superior pollutant removal by *G. candidum* achieved reductions of 46.9% in BOD, 16.9% in COD and 64.9% in O&G, while *C. rugosa* achieved a reduction of 44.6% in BOD, 13.9% in COD and 50.7% in O&G, demonstrating its capability to efficiently break down organic matter. These findings show that the utilisation of locally sourced fungi is not only an economical alternative to traditional POME treatment methods but also promotes environmental sustainability by using naturally adapted organisms. This strategy aligns with the growing importance of site-specific microbial solutions and further highlights the critical roles of strain selection for the optimisation process in the biodegradation of POME using fungi.

The study by Binma-Ae et al. (2021) further highlighted the potential of thermotolerant fungi in enhancing POME biodegradation through the production of cellulase and xylanase enzymes. In the study, *Aspergillus* sp. was applied to raw POME with initial pollutant concentrations of COD at 45,200 mg/L and BOD at 17,000 mg/L. After six days of treatment under optimised conditions at a temperature of 45°C and an agitation speed of 200 rpm, the fungus achieved 31.0% reduction in COD and 49.1% reduction in BOD. Although the removal efficiencies were moderate compared to other fungal strains, these findings emphasise the suitability of thermotolerant fungi as pretreatment agents, especially for reducing pollutant loads in

a high-temperature environment. The capability of this thermotolerant fungus also suggests that it can serve as a valuable pretreatment agent in multi-stage POME treatment systems, particularly when it is integrated with subsequent processes to achieve discharge standards.

The investigation conducted by Bakar et al. (2022) provides further evidence of the effectiveness of fungi in POME treatment. Using *A. flavus* under controlled conditions with a HRT of five days, at a temperature of  $35 \pm 2^\circ\text{C}$  and an agitation speed of 180 rpm, the treatment achieved pollutant removal efficiencies of 36.0% for COD, 48.6% for BOD and 60.0% for TSS. The notable TSS reduction highlights the strong potential of *A. flavus* in minimising suspended solids, thereby reducing sediment load in the effluent discharge. Furthermore, the study incorporated co-fermentation with *Lysinibacillus* sp., which improved pollutant degradation as well as facilitated waste valorisation. When POME was co-cultured with empty fruit bunches at a ratio of 7:3, it produced a maximum calorific energy value of 26.71 MJ/kg, allowing for zero wastewater discharge in a single day. These findings highlight the combined benefits of pollution removal and sustainable biomass fuel generation, promoting sustainable consumption and production patterns and thus, advancing environmentally friendly strategies for palm oil waste management.

The study conducted by Thegarathah et al. (2022) provided further insights into the efficiency of fungal-based treatment systems, specifically emphasising turbidity removal. The evaluation of *A. niger* immobilised on coconut husk through submerged fermentation under controlled conditions demonstrated a remarkable turbidity removal efficiency, achieving a 96.2% reduction from an initial turbidity of 3,980 formazin attenuation unit (FAU) within a HRT of seven days. The process was carried out at an optimised temperature of  $32 \pm 2^\circ\text{C}$  with an agitation speed of 150 rpm, conditions that significantly enhanced fungal performance. These findings highlight the importance of immobilisation in enhancing fungal stability and activity, while simultaneously demonstrating the cost-effectiveness of utilising agro-waste carriers like coconut husk for large-scale applications. The impressive reduction in turbidity highlights the potential of *A. niger* as an effective biological agent for final polishing stages in POME treatment. Moreover, the study reinforces the critical role of optimising operational parameters, such as temperature stability and adequate mixing, in driving fungal performance. Collectively, these results demonstrate the feasibility of *A. niger* as a sustainable alternative and strategy for enhancing conventional POME treatment systems.

The study by Suttinun et al. (2025) significantly deepened the understanding of fungal degradation mechanisms and the influence of the process conditions in POME treatment. They isolated *Thermomyces lanuginosus* TSP3-2, a thermophilic fungus that produces polyphenol oxidase and tested its capability to degrade phenolic compounds under varying pH values and temperatures. The fungus demonstrated significant efficiency under optimised neutral to alkaline with pH values of 6.5–8.0 and thermophilic temperature ranged from  $60^\circ\text{C}$  to  $70^\circ\text{C}$ , achieving up to 79% removal of phenol. This high performance was directly correlated with its peak polyphenol oxidase activity, which reached approximately 91.7 U/L at pH 7. Notably, *T. lanuginosus* TSP3-2 induced partial depolymerisation of phenolics and simultaneously yielded valuable co-products, including xylanase and fungal biomass protein. The findings underscore the critical role of the operational parameters, particularly pH and temperature, in maximising enzymatic phenolics removal. More broadly, it also highlights the dual potential of fungal systems to both detoxify pollutants and produce valuable biomolecules.

#### COMPARATIVE ASSESSMENT BETWEEN CONVENTIONAL POME TREATMENT AND FUNGAL-BASED TREATMENT

POME treatment has traditionally depended on conventional treatment methods, which have served the palm oil industry for decades. Although these conventional methods are well-established, there is a growing need for more effective and sustainable approaches due to their operational and environmental limitations. Fungal-based treatment has emerged as a potential alternative, with a higher pollutant removal efficiency, shorter treatment times and better alignment with current sustainability goals. Table 3 illustrate a comparative summary of key performance parameters between conventional treatment and fungal-based treatment. The table highlights the differences in pollutant removal efficiency, HRT and operational conditions, providing a clearer perspective for understanding the distinct roles of the both treatment systems play in addressing POME management challenges.

Conventional treatment systems, such as ponding systems and anaerobic digestion, providing a straightforward approach for removing pollutants. However, these treatment methods often fail to achieve consistently high removal efficiencies, particularly for more recalcitrant organic pollutants. For example, ponding systems demonstrate effectiveness in

reducing biodegradable organic pollutants in POME, achieving up to 90.0% BOD removal under optimal operating conditions (Jumadi et al., 2020; Lokman et al., 2021). In contrast, their efficiency is considerably lower for COD, typically ranging from 50.0% to 70.0% (Yunus et al., 2015). Ponding systems also struggle with a consistent removal of O&G, necessitating the implementation of additional tertiary treatment processes to comply with regulatory the discharge standards. In comparison to conventional methods, fungal-based treatments utilising species such as *A. niger* and *E. nidulans* achieve superior efficiency, with BOD removal ranging between 80%–90%, along with COD removal between 60%–90% (Bala et al., 2018; Suseela & Muralidhar, 2018). Furthermore, *R. oryzae* ST 29 was reported to achieve up to 98.6% O&G removal, significantly outperforming conventional systems (Prasertsan & Binmaeil, 2018).

Although conventional treatment systems are valued for their reliability, their extended HRT severely compromise the overall efficiency, necessitating an improvement for more efficient and time-effective alternatives. Ponding systems typically require a notably long retention time, usually exceeding 60 days, to significantly reduce pollutant levels before the effluent can be discharged into the environment (Mohammad et al., 2021; Sabiani et al., 2024). While anaerobic digestion can shorten the treatment duration to 3,060 days, this timeframe remains inadequate to meet the rapid operational requirements of modern industries (Lokman et al., 2021; Murti et al., 2024; Zainal et al., 2022). Fungal-based treatment systems offer a significantly shorter treatment duration than traditional methods, typically ranging from 5 to 10 days (Bakar et al., 2022; Binma-Ae et al., 2021; Ganapathy et al., 2019; Neoh et al., 2014; Peace & Ome, 2014; Prasertsan & Binmaeil, 2018; Riddibud et al., 2024; Thegarathah et al., 2022). Moreover, the shorter treatment process also reduces the amount of land required, making fungal-based systems more practical and suitable option for operation in regions with limited space.

Ponding systems remain attractive due to their low initial investment, minimal technical requirements and reliance on natural processes. Consequently, major expenses are limited to land acquisition and periodic maintenance. However, the low operational complexity of these systems comes with a low efficiency, as they often require prolonged retention times and large land areas (Nadzim et al., 2023). Similarly, while the anaerobic digestion offers improved efficiency, it remains vulnerable to process instability and still requires significant treatment time. On the other hand, fungal-based treatment provides an advanced alternative with major improvements

in efficiency and environmental sustainability, but these benefits come along with a higher operational complexity. These systems typically rely on bioreactors or other controlled environment structures, which require skilled labour, precise monitoring and specialised equipment to optimise fungal growth and enzymatic activity (Latif et al., 2023; Pundir et al., 2024). Consequently, while fungal-based systems present a transformative opportunity, transitioning them to full industrial application will critically depend on progress in process optimisation and techno-economic feasibility.

Nevertheless, a critical bias must be acknowledged when comparing the fungal-based treatments with conventional methods. Most fungal studies have been reported based on laboratory-scale experiments with ideal parameters for nutrient supply, aeration, pH and temperature, enhancing fungal growth and enzymatic activity in shorter treatment durations. A controlled laboratory environment often accelerates treatment and maximises pollutant removal, potentially overestimating their performance relative to real-world operations. In contrast, existing ponding and anaerobic systems are already implemented at a full-scale, facing environmental fluctuations, variable hydraulic loading and long-term operational issues that are hard to simulate in a laboratory. Therefore, the scalability, stability under non-sterile field conditions and economic feasibility of fungal treatments still need to be fully validated. This validation is essential for making meaningful comparisons with established treatment systems in terms of efficiency, treatment duration, complexity and operational costs.

#### CHALLENGES IN INTEGRATING FUNGAL-BASED POME TREATMENT

The use of fungi for treating POME has attracted considerable attention for its potential to deliver high efficiency while promoting environmental sustainability. Nonetheless, this promising method faces various challenges and its wider implementation depends on overcoming key technical, economic and operational issues. Simultaneously, the future prospects of fungal-based treatment hold considerable potential for POME treatment, driven by advancements in biotechnology, environmental policies and industrial collaboration.

A key challenge in utilising fungi for POME treatment lies in maintaining the optimal environmental conditions necessary for consistent and efficient pollutant degradation. The fungal strain has desired operating conditions,

TABLE 2. REMOVAL EFFICIENCY OF POME TREATMENT USING FUNGI

Fungi	Initial concentration	Removal efficiency	Operational parameter	Remarks	References
<i>Emmericella nidulans</i> NFCCI 3643		COD: 80.3% BOD <sub>5</sub> : 88.2% O&G: 87.3%			
<i>Trichoderma reesei</i>		COD: 59.3% BOD <sub>5</sub> : 68.2% O&G: 59.1%			
<i>Trichoderma harzianum</i>	COD: 79,980 mg/L BOD <sub>5</sub> : 39,476 mg/L O&G: 209 mg/L	COD: 64.8% BOD <sub>5</sub> : 88.2% O&G: 52.6%	HRT: 5 days Temperature: 30°C Agitation speed: 150 rpm	Enhanced biodegradation, potentially from synergistic enzyme action on organic load.	Suseela & Muralidhar (2018)
<i>Aspergillus niger</i>		COD: 71.1% BOD <sub>5</sub> : 77.6% O&G: 71.2%			
<i>Aspergillus fumigatus</i>		COD: 61.9% BOD <sub>5</sub> : 63.3% O&G: 61.2%			
<i>Rhizopus oryzae</i> ST29	COD: 144,000 mg/L O&G: 10,000 mg/L TS: 71,500 mg/L	COD: 60.0% O&G: 98.6% TS: 52.9%	HRT: 5 days Temperature: 45°C Agitation speed: 200 rpm pH: 4.5	Strong lipase secretion enabled outstanding O&G removal; enzyme production optimal at high temperature and acidic pH.	Prasertsan & Binnmaeil (2018)
<i>Meyerozyma guilliermondii</i>	COD: 35,983.5 mg/L TN: 833.4 mg/L NH <sub>3</sub> -N: 91.7 mg/L TOC: 3,119 mg/L Phosphate: 581.7 mg/L O&G: 3,750 mg/L	COD: 72.0% TN: 49.2% NH <sub>3</sub> -N: 45.1% TOC: 46.6% Phosphate: 60.6% O&G: 92.4%	HRT: 7 days Temperature: 30°C Agitation speed: 150 rpm pH: 4.5	Demonstrated multi-pollutant removal; potential for eco-safe discharge and biofertiliser reuse.	Ganapathy et al. (2019)
<i>Trametes elegans</i> (PP17-06)		Decolourisation: 55.6%	HRT: 8 days Temperature: 25°C Agitation speed: 150 rpm pH: 7	White-rot fungus utilises manganese peroxidase for lignin and phenolics colorant breakdown.	Riditbud et al. (2024)
<i>Trametes hirsuta</i> AK 04	Phenolics: 1,277 ± 37 mg/L COD: 56,416 ± 2412 mg/L	Dephenolisation: 85.0% COD: 80.0%	HRT: 4 days Temperature: 29 ± 2°C	Immobilised on OPF in a bioreactor; improved phenolics removal boosted post-treatment biogas yield.	Kietkwanboot et al. (2022)
<i>Curvularia clavata</i>	Colour: 3,793 ± 352 ADMI COD: 930 ± 68 mg/L NH <sub>3</sub> -N: 71 ± 5 mg/L Phosphate: 16.83 ± 0.32 mg/L	Decolourisation: 80.0% COD: 41.0% NH <sub>3</sub> -N: 65.0% Phosphate: 91.0%	HRT: 5 days Temperature: 27 ± 1°C Agitation speed: 150 rpm pH: 5	Effective polyphenol and lignins reduction; also detoxifies and lowers nutrient pollution.	Neoh et al. (2014)

TABLE 2. REMOVAL EFFICIENCY OF POME TREATMENT USING FUNGI (continued)

Fungi	Initial concentration	Removal efficiency	Operational parameter	Remarks	References
<i>Candida rugosa</i>	BOD: 16,280 ± 25 mg/L COD: 78,750 ± 41 mg/L O&G: 5,165 ± 08 mg/L	BOD: 44.6% COD: 13.9% O&G: 50.7%	HRT: 6 days Temperature: 30°C Agitation speed: 200 rpm pH: 8	Cost-effective local yeast; moderate pollutant reduction, higher O&G degradation; good for lipid-rich waste.	Peace & Ome (2014)
<i>Aspergillus sp.</i>	COD: 45,200 mg/L BOD: 17,000 mg/L	COD: 31.0 % BOD: 49.1 %	HRT: 6 days Temperature: 45°C Agitation speed: 200 rpm	Moderate efficiency; recommended for thermotolerant pretreatment.	Binma-Ae et al. (2021)
<i>Aspergillus flavus</i>	COD: 36.0% BOD: 48.6% TSS: 60.0%		HRT: 5 days Temperature: 35 ± 2°C Agitation speed: 180 rpm	Effective TSS removal; potential in the sediment reduction process.	Bakar et al. (2022)
<i>Aspergillus niger</i>	Turbidity: 3,980 FAU	Turbidity: 96.2%	HRT: 7 days Temperature: 32 ± 2°C Agitation speed: 150 rpm	Effective turbidity reduction; potential for final polishing.	Thegarathah et al. (2022)
<i>Thermomyces lanuginosus</i> TSP3-2		Dephenolisation: 79%	pH: 7.0	Effective phenolics removal; optimal at high temperature and neutral to alkaline pH.	Suttinun et al. (2025)

Note: COD - chemical oxygen demand; BOD - biological oxygen; TSS - total suspended solids; NH<sub>3</sub>-N - ammoniacal nitrogen; O&G - oil and grease; TN - total nitrogen; POME - palm oil mill effluent; TS - total solids; HRT - hydraulic retention time; TOC - total organic carbon.

TABLE 3. COMPARATIVE ASSESSMENT FOR POME BETWEEN CONVENTIONAL TREATMENT METHODS AND FUNGAL-BASED TREATMENT

Parameter	Ponding system	Anaerobic digestion	Fungal-based treatment
BOD removal	Up to 90.0% (optimal conditions) (Jumadi et al., 2020; Lokman et al., 2021)	80%–95% (Ramón et al., 2024)	80%–90% (Singh et al., 2021; Suseela & Muralidhar, 2018)
COD removal	50%–70% (Arisht et al., 2020; Yunus et al., 2015)	50%–70% (Ramón et al., 2024)	60%–90% (Kietkwanboot et al., 2022; Prasertsan & Binmaeil, 2018; Suseela & Muralidhar, 2018)
O&G removal	Inconsistent, often fails (Jumadi et al., 2020; Lokman et al., 2021)	Moderate (Muhammad et al., 2023; Soo et al., 2022)	Up to 98.6% (Kietkwanboot et al., 2022; Prasertsan & Binmaeil, 2018; Suseela & Muralidhar, 2018)
Treatment duration	60–90 days (Mohammad et al., 2021; Sabiani et al., 2024)	30–60 days (Lokman et al., 2021; Murti et al., 2024; Zainal et al., 2022)	5–10 days (Bakar et al., 2022; Binma-Ae et al., 2021; Ganapathy et al., 2019; Kietkwanboot et al., 2022; Prasertsan & Binmaeil, 2018; Riddibud et al., 2024; Suseela & Muralidhar, 2018; Thegarathah et al., 2022)
Key limitations	Long retention time (Nadzim et al., 2023) Requires a larger land area (Soo et al., 2022; Yu et al., 2024)	Process instability, sensitive to environmental changes (Wu et al., 2010) Insufficient COD removal (Ramón et al., 2024)	Higher initial cost (Latif et al., 2023) Limited to lab / pilot scale, requires optimisation for large-scale application (Pundir et al., 2024)

Note: BOD - biological oxygen demand; COD - chemical oxygen demand; O&G - oil and grease; POME - palm oil mill effluent.

including appropriate temperature, pH level, HRT, aeration or agitation, nutrient availability, fungal strain selection, organic load and pollutant concentration for optimal growth and metabolic activity. Changes in these operating conditions, which usually happen in large-scale industrial operations, can greatly impact the efficiency of the fungal treatment systems. Additionally, POME is a complex and inconsistent effluent, with its composition varying based on the palm oil milling process, raw materials, and seasonal (Ng et al., 2023; Shakir et al., 2016; Sukor et al., 2024; Tambe et al., 2024). This variability requires careful selection and adaptation of fungal strains to suit the specific properties of the effluent, making the design and operation of treatment systems more challenging.

Scaling up fungal-based treatment systems for industrial applications presents various interconnected challenges. While laboratory studies have demonstrated promising results, translating these findings into large-scale operations involves overcoming technical, financial, and operational barriers (Aiduang et al., 2022; Langton et al., 2022; Sar et al., 2024; Singh et al., 2021; Thirumalaivasan et al., 2024). For instance, designing and constructing bioreactors capable of supporting fungal growth and enzymatic activity on a commercial scale requires significant investment and specialised expertise. Moreover, maintaining a sterile or semi-sterile environment to prevent contamination by competing with other microorganisms becomes increasingly difficult as the system size grows. Such contamination decreases the efficiency of the treatment and destabilises the system by competing with the desirable fungal strains.

Economic viability is another crucial challenge influencing the adoption of fungal-based POME treatment. While these systems provide long-term cost-benefits by effectively improving pollutant removal, reducing treatment times and resource recovery, the initial setup costs for system integration could pose a financial challenge for many small and medium-sized palm oil mills. Transitioning to the implementation of fungal treatment into the existing current system requires a process of modifying or transitioning the current systems, which could further increase the costs. Financial constraints, along with a lack of awareness or technical expertise among mill operators, could delay the adaptation of fungal-based technology. Careful and strategic planning can address these challenges over time. The successful widespread adoption of advanced wastewater treatment hinges on providing financial incentives, enacting clear regulatory frameworks, and sufficient technical expertise (Karno et al., 2024).

## THE PROSPECTS OF FUNGAL-BASED TREATMENT SYSTEM FOR POME

Despite the challenges reported earlier, the prospects of POME treatment using fungi remains highly promising approaches for wastewater treatment. Innovations in fungal biotechnology, including genetic engineering and adaptive evolution, are driving the creation of resilient and highly efficient fungal strains (Kersey et al., 2020; Salazar-Cerezo et al., 2023; Sandberg et al., 2019; Tiwari & Park, 2024; Yang et al., 2024). By modifying these strains to withstand harsh environments, target specific pollutants, or produce valuable by-products, fungal treatment system becomes more adaptable and effective. Advanced bioreactor designs, which are integrated with the existing treatment systems such as membrane bioreactors and fluidised bed reactors, opens up possibilities for hybrid systems that combine the strengths of multiple approaches, including enhanced nutrient distribution, improved oxygen transfer, and increased substrate contact. These collective improvements can optimize fungal growth, metabolic activity, and overall treatment efficiency.

Environmental concerns and strict regulations are driving the adoption of innovative wastewater treatment technologies, particularly for the fungal-based systems. These systems offer sustainable and efficient solutions for treating challenging industrial effluents like POME, aligning with the increasing need for eco-friendly approaches. Successful implementation requires collaboration between researchers, industries and policymakers. Researchers contribute expertise in fungal technology, industries provide real-world or practical insights and infrastructure and policymakers establish supportive regulations and financial incentives. Incentives such as subsidies and tax breaks can encourage the adoption and implementation of fungal-based treatment technologies (Ahmed et al., 2023; Cagno et al., 2022; Chen et al., 2023; Fontecha et al., 2022; Pořkus et al., 2021). This integrated approach not only helps industries meet the environmental standards but also contributes to broader sustainability goals, including reducing the environmental impact of industrial activities and promoting a circular economy.

Fungal-based POME treatment systems offer economic benefits through the recovery of valuable by-products. As fungi consume POME, they generate high-value products like enzymes, organic acids, and bioethanol (Amini et al., 2022; Chai et al., 2022; Chatterjee & Venkata Mohan, 2022; Mahongnao et al., 2023; Wang et al., 2021; Yan et al., 2024). These by-products not only enhance sustainability but also provide additional revenue for industries,

making the treatment more cost-effective. Enzymes, organic acids, and bioethanol produced by fungi have diverse applications in various sectors, creating significant market opportunities. By recovering these by-products, industries can offset the treatment costs and even generate profit. This aligns with the circular economy principles of waste valorisation, reducing environmental impact and promoting sustainability. Furthermore, by-product recovery encourages investment in fungal-based technologies, driving further research and development to optimise production and expand the range of recoverable products. This dual benefit of environmental protection and economic gain makes fungal-based POME treatment a highly promising and attractive option for the industries.

### CONCLUSION

In conclusion, the treatment of POME using fungi presents a sustainable and transformative solution for mitigating the environmental challenges faced by the palm oil industry. Fungal-based POME treatment offers enhanced pollutant removal efficiency, shorter treatment durations and reduced land requirement compared to the conventional methods. Their distinctive pollutant removal mechanisms, combined with substrate versatility and adaptability to harsh conditions, enable them to degrade complex organic pollutants in POME even under extreme environments. All these advantages present an opportunity for the palm oil industry and policymakers to develop supportive regulatory frameworks that encourage the adoption of fungal-based systems within the existing wastewater management, ensuring compliance with the both national standards and global sustainability goals. These findings also highlight the need for future research, focusing on refining potential fungal strains, optimising bioreactors and assessing the techno-economic feasibility to successfully transform the laboratory-scale promise into industrial implementation. Therefore, through continued innovation, supportive policies and cross-sector collaboration, fungal-based POME treatment has the potential not only to mitigate the severe environmental impacts of POME but also to transform the palm oil industry toward a greater, environmentally sustainable future.

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