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Resource recovery and treatment of wastewaters using filamentous fungi

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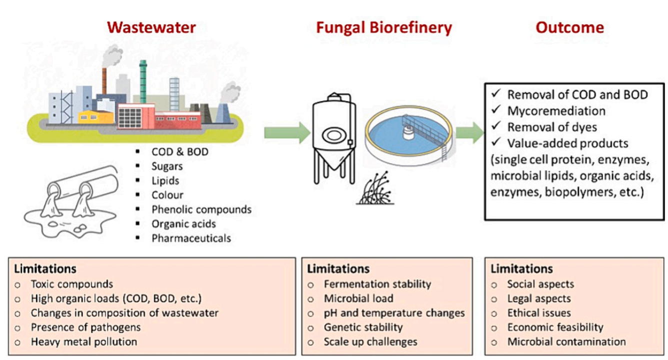
HIGHLIGHTS

- Industrial wastewaters are feedstocks for filamentous fungal biorefineries.
- Filamentous fungi, with their diverse enzymatic profiles, offer effective solutions for wastewater treatment.
- Filamentous fungi exhibit significant potential in absorbing and sequestering metal contaminants from industrial wastewaters.
- Filamentous fungi contribute to the bioeconomy by producing valuable byproducts.
- Microbial contamination, economical challenges, ethical, legal and social hinders are still limitations for this process.

GRAPHICAL ABSTRACT



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ABSTRACT

Industrial wastewater, often characterized by its proximity to neutral pH, presents a promising opportunity for fungal utilization despite the prevalent preference of fungi for acidic conditions. This review addresses this discrepancy, highlighting the potential of certain industrial wastewaters, particularly those with low pH levels, for fungal biorefinery. Additionally, the economic implications of biomass recovery and compound separation, factors that require explicit were emphasized. Through an in-depth analysis of various industrial sectors, including food processing, textiles, pharmaceuticals, and paper-pulp, this study explores how filamentous fungi can effectively harness the nutrient-rich content of wastewaters to produce valuable resources. The pivotal role of ligninolytic enzymes synthesized by fungi in wastewater purification is examined, as well as their ability to absorb metal contaminants. Furthermore, the diverse benefits of fungal biorefinery are underscored, including the production of protein-rich single-cell protein, biolipids, enzymes, and organic acids, which not only enhance environmental sustainability but also foster economic growth. Finally, the challenges associated with scaling up

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fungal biorefinery processes for wastewater treatment are critically evaluated, providing valuable insights for future research and industrial implementation. This comprehensive analysis aims to elucidate the potential of fungal biorefinery in addressing industrial wastewater challenges while promoting sustainable resource utilization.

1. Introduction

Water is an essential component of life, serving as a fundamental and indispensable resource for all living organisms. Any reduction in its availability or deterioration in its quality can result in severe harm to the environment, with potentially catastrophic consequences (Michalska et al., 2021). The available sources of water in the environment are being progressively contaminated by human and industrial activities, including agricultural production, mining, refining, heavy metal usage, leather and textile production, food processing, chemical manufacturing, pharmaceutical production, dyeing, pesticide usage, and detergent manufacturing, among others. Wastewater generated from these different industrial processes is a major environmental concern due to its high pollutant load and low degradability (Negi and Das, 2023). It is difficult to point out the specific industry or sector that causes the most harm to the environment. The streams that are generated by the pharmaceutical industry, although low in absolute volumes, are considered highly polluting due to the presence of pharmaceuticals in ground- and surface water. Meanwhile, other industries such as energy, paper-pulp, and textile production consume the most water but are often committed to sustainable water management and investing in new technologies for wastewater treatment to prevent water pollution (Michalska et al., 2021).

To ensure that the effluent water is as clean as possible and to eliminate any solids that may pose a threat to human health and the environment, industrial wastewater must undergo the treatment processes prior to be either reused or discharged directly into the environment. This process is essential in order to meet the necessary standards for clean water (More et al., 2010; Negi and Das, 2023). Conventional wastewater treatment methods (physical and chemical methods) have limitations such as high cost, high energy consumption, and the production of hazardous byproducts due to the use of chemicals that affect removal treatment of specific pollutants from industrial wastewater. One of the solutions is to move towards the utilization of affordable, eco-friendly, and harmless approaches such as biological degradation, remediation, or de-colouration using various types of microorganisms (Dhanavade and Patil, 2023). Bacteria, fungi, and algae are frequently used in the industrial sector for biological wastewater treatment due to their cost-effectiveness, easy-to-use operating systems, energy efficiency, high biomass volume, and ability to produce value-added products that can be utilized in energy production and other applications (Negi and Das, 2023; Sankaran et al., 2010). Bacterial strains are the most frequently employed microorganisms in biological wastewater treatment systems for eliminating organic pollutants. In contrast, filamentous fungi have received much less attention than bacteria for the purpose of wastewater treatment while fungal strains can produce several degradative enzymes and surface proteins that play important role during biodegradation or biosorption of pollutants existing in the wastewater (Negi and Das, 2023). Due to their heterotrophic nature, filamentous fungi have developed a diverse range of enzyme systems to sustain themselves through parasitic or saprotrophic means. They can be found in a broad range of environmental conditions and on numerous substrates. Fungi possess the ability to naturally decompose organic materials, and their capability to convert organic waste into useful compounds is being harnessed to produce valuable products (Singh and Vyas, 2021). Moreover, filamentous fungi have more advantages in comparison to other types of microorganisms. In addition, recent research has shown that filamentous fungi have great potential for treating industrial wastewaters. For instance, filamentous fungi can survive better than bacteria under the harsh conditions, produce higher biomass, and their isolation procedure is not as difficult as bacterial ones (Dhanavade and Patil, 2023).

The aim of this review was to critically examine the potential of utilizing fungal biorefinery processes for the treatment of industrial wastewater. The review focused on evaluating how filamentous fungi can leverage various industrial wastewaters, particularly those with low pH levels, to produce valuable bioproducts. By exploring the capabilities of ligninolytic enzymes synthesized by the fungi in purifying wastewater and sequestering metal contaminants, this review sought to highlight the dual benefits of environmental sustainability and economic viability. The overarching goal was to provide a comprehensive understanding of the opportunities and challenges associated with scaling up fungal biorefinery processes for effective industrial wastewater treatment.

2. Filamentous fungi

Fungi play a crucial role in breaking down waste materials that makes them a vital part of the complex network in the various ecosystems (Sharma, 2023). Many genera of filamentous fungi such as *Phanerochaete*, *Pleurotus*, *Penicillium*, *Fusarium*, *Ganoderma*, *Lepiota*, *Trametes*, *Daldenia*, and *Aspergillus* are suitable candidates for the treatment of industrial wastewater containing dyes due to their capability in bioaccumulation, biodegradation, and biosorption (Abd El-Zaher, 2010; Kunjadia et al., 2016; Yamuna et al., 2017). For example, *Aspergillus ochraceus* NCIM-1146 has been studied for its enzymatic potential in dye removal through the production of a thermostable blue laccase. This strain was able to effectively decolourize Reactive Golden Yellow HER, Reactive Navy Blue HER, and Methyl Orange by 56–90 % (Telke et al., 2010). Actively growing cultures of fungi and consortia of fungi with other microorganisms (Kurade et al., 2023), cell-free extract of filamentous fungi can be used for dye decolourization (Michalska et al., 2021; Ryu et al., 2017). Fungal ligninolytic enzymes such as laccases or multi-copper oxidases (E.C. 1.10.3.2.), azoreductases (EC 1.7.1.6), and peroxidases (EC 1.11.1.x) have been reported responsible for pollutant removal in industrial effluent wastes. Laccases are able to mostly oxidize phenolic and non-phenolic compounds and have distinctive advantages, including cofactor-free activity and non-specific action for oxidation of xenobiotic materials that make them for appropriate for mycoremediation of olive mill waste, coffee pulp waste and other industrial and agricultural wastes; however, azoreductases and different peroxidases (manganese peroxidases, lignin peroxidases (diaryl propane oxygenases), and versatile peroxidases) can catalyse the decontamination reactions in the presence of their suitable cofactors (Dhanavade and Patil, 2023). Another form of filamentous fungi that attracts researchers' attention to be used for mycoremediation is mycelial pellets or granules which are spherical and scattered fungal mycelial cells with biosorption and other biological capabilities. Due to the specific features of mycelial pellets such as porosity, quick adaptability to different conditions, rapid growth, net-like texture, and efficient dewatering capabilities, they can be effectively employed for sludge dewatering, biosorption, and biomass aggregation (Li et al., 2020; Veiter et al., 2018). For instance, research is being conducted on the potential use of mycelial pellets from *R. oryzae* as biosorbents to eliminate copper and cadmium ions from water solutions (Fu et al., 2012). Mycelial pellets are produced through two different ways: non-aggregative and aggregative phases. During the aggregative phase, the spores come together to form pellets, whereas in the non-aggregative phase, a single spore produces a pellet with aeration and agitation;

however, only some fungal strains are able to produce pellets successfully depending on experimental factors such as inoculum concentration, growth medium composition, and growth conditions (Veiter et al., 2018).

In addition to mycelial pellets, recently a low-cost and environmentally friendly mycoremediation process has been developed for the rapid removal of a highly toxic industrial Congo red using native filamentous fungus, *Penicillium crustosum* PWWS-6, immobilized on agar plugs. The process involves the biosorption of Congo red followed by mineralization, as evidenced by the expression of various extracellular enzymes such as azoreductase, veratryl alcohol oxidase, NADH-DCIP reductase, and lignin peroxidase at the molecular level during the decolourization experiment. The process underwent optimization, with incubation time set at 16 h, temperature at 27 °C, and inoculum volume at 6 fungal discs, utilizing statistical techniques. This optimization resulted in a notable enhancement in the rate of dye removal and a reduction in the decolourization period. This study has been suggested the potential of immobilized *P. crustosum* PWWS-6 as an effective agent for the treatment of toxic pollutants existing in the wastewater (Sharma et al., 2021).

Mycoremediation of industrial effluent wastes can be affected by several operational conditions such as pH value, temperature, pollutant concentration, carbon and nitrogen type and amounts, oxygen, mass transfer and agitation rate. Therefore, it is crucial to carefully adjust these parameters to ensure the acquisition of reliable data and results. Among these parameters, pH plays a critical role during mycoremediation and essentially affects the use of filamentous fungi for industrial purposes as under highly acidic (pH 2.0–4.0) or alkaline conditions (pH 10), fungal-mediated systems tend to fail rapidly (Dhanavade and Patil, 2023).

2.1. Biosorption in filamentous fungi

Filamentous fungi have the ability to clean up organic and inorganic pollutants, as well as heavy metals, using biosorption and bio-reduction techniques. Biosorption is when living substances capture pollutants through adsorption processes. This process involves microbial biomass passively or actively trapping organic and inorganic substances in water, allowing for the safe and responsible removal of toxins and promoting a clean environment. The process of biosorption can occur in two ways: it can either be dependent on metabolism or independent of metabolism (Legorreta-Castañeda et al., 2020). The cell walls of filamentous fungi contain various functional groups that are useful for biosorption, including hydroxyl, amine, and carboxyl groups. Fungal biomass has a high cell wall content, which makes it a promising material for biosorption. The more metal-binding functional groups there are on the surface of the cell wall, the better the ability of fungi to capture metals. Filamentous fungi are excellent biosorbents because they have a high tolerance to metals and can thrive in conditions with low pH, which is often found in wastewater containing zinc, such as acid mine drainage and industrial wastewater from battery manufacturing (Legorreta-Castañeda et al., 2020; Negi and Das, 2023). In addition to viable cells of filamentous fungi, dead cells of these microorganisms are considered as popular biosorbents for heavy metals and dyes removal from wastewater as no nutrimental, growth, and other cares are required. Moreover, long-term storage of dead biosorbents is certainly easier than viable biosorbents (Negi and Das, 2023).

3. Wastewater

3.1. Oily wastewaters

3.1.1. Olive oil industry wastes

Olive oil has been a predominant component of the Mediterranean diet. International Olive Council (IOC) statistics indicate triplication of its production in the last 60 years, reaching 3.02 million tonnes the 2020/21 crop year. The same year, the EU member states contributed ~74 % of the world total. Provisional data for 2021/22 point to an increase (+11.0 %) in production for a volume of 3.4 million tonnes. Estimates for the 2022/23 crop year put production at 2.8 million tonnes (−17.6 %). World consumption of olive oil has increased in a faster rate than production over the last three crop years (2019/20, 2020/21 and 2021/22) with an output of ~3.1 million tonnes (International Olive Council, 2023). Its growing popularity is linked to several health-promoting properties due to the presence of bioactive compounds (Mastralexi and Tsimidou, 2021).

However, this production is associated with the creation of massive quantities of polluting and difficult to handle waste streams, known as olive mill wastes (OMWs). Upon each of the technology used to extract the olive oil – the so-called traditional discontinuous press extraction that gave way to the continuous process, which uses a two- or a three-phase centrifugal extraction system – olive pomace, a solid waste stream, and olive mill wastewater (OMWW) are the two main waste streams. A vital point is that the type and amount of OMWWs produced depend on the technology used to extract the olive oil. The three-phase mills generate the highest output of OMWW (90–110 L/100 kg of processed olives) (50 %) along with olive pomace (30 %) and olive oil (20 %). Corresponding waste streams of the two-phase mills are 200 L/ton of OMWW and a semi solid two-phase olive-mill waste (TPOMW) (10 L/100 kg olives), which is 60 % higher than the respective stream from the three-phase system. TPOMW is difficult to manage because its pollutant load is more concentrated (Dermeche et al., 2013; El Mekawy et al., 2014; Khdair and Abu-Rumman, 2020; Zahi et al., 2022).

OMWW is an acidic emulsion (pH value of 4 to 6) with an intense brown-to-black colour and average biological oxygen demand (BOD) and chemical oxygen demand (COD) of 40–95 g/L and 50–180 g/L, respectively. In addition to water (83–92 %), sugars, organic acids, lipids, nitrogen compounds, and phenolic compounds comprise the majority of OMWW. On the other hand, TPOMW is a thick sludge (moisture content of 65–75 %), made up of vegetative water, olive fruit pulp, and stone fragments. The major compositions are cellulose, hemicellulose, and lignin, but there are also considerable amounts of lipids, proteins, and phenolic compounds. TPOMW and olive pomace from the three-phase system have higher ash contents (1.70–4 % and 1.42–4 %, respectively), compared to OMWW. Potassium is the main element in these streams, followed by calcium and sodium, similarly to OMWW (El Mekawy et al., 2014; Hamimed et al., 2021).

Due to their phytotoxicity and antimicrobial activity, olive phenols are substantial contributors to the pollution caused by OMWWs in soil, aquatic and air environment. According to literature data, the phenolic compounds identified in OMWWs are low and high molecular weight components that belong to the groups of phenyl alcohols, phenolic acids, secoiridoid derivatives, and flavonoids. These chemicals in OMWWs vary depending on their polarity, the olive cultivar, fruit ripeness, climate, agronomic conditions, storage conditions before extraction, and processing method. Hydroxytyrosol is the main phenolic component of the OMWW. Tyrosol and hydroxytyrosol, as well as p-coumaric and, to a lesser extent, vanillic acid, are the most prevalent phenolic compounds in TPOMW (Dermeche et al., 2013; Hamimed et al., 2021; Zahi et al., 2022).

The physicochemical characteristics of OMWWs have a negative impact on management and disposal procedures. Research over the past few decades has shown that bioremediation is an effective detoxification strategy. In this direction, among other microorganisms, a number of fungi, including *Phanerochaete* spp., *Pleurotus* spp., *Panus tigrinus*, *Geotrichum* spp., *Lentinula edodes*, *Trametes versicolor*, and *Aspergillus* spp., may have the ability to lower the COD value of the OMWWs. Also, biotechnological approaches in conjunction with microbial detoxification of OMWWs may result in the production of valuable biomass or value-added products (Abrunhosa et al., 2013; Sar et al., 2020b). For example, this is the case of the use of filamentous and white rot fungi belonging *Basidiomycetes* for the biological detoxification of OMWWs and the production of important amounts of commercial enzymes (e.g., lipase and laccase). However, there are still considerable obstacles to overcome, mainly, the existence of inhibitory substances such as phenolic compounds, high acidity, and seasonality. Suitable chemical, physical, or biological pretreatments as well as blending with other waste streams could give promising results for OMWWs valorisation in a cost-effective way. Moreover, the selection of single or mixed cultures of indigenous or commercial fungal strains could help overcome the toxic effect of phenolic compounds in OMWWs (De Leonardis et al., 2023; Hamimed et al., 2021; Sar et al., 2020b).

3.1.2. Palm oil industry wastes

The world's most significant oil crop is the oil palm tree, *Elaeis guineensis*, which provides >50 % of all traded vegetable fats and oils. Oil palm fruit is used to make two different types of oils: lauric oil, which is made from the palm kernel, and palm oil, which is made from the fibrous mesocarp. Malaysia and Indonesia produce over 80 % of the world's palm oil. The five greatest palm oil producers worldwide are Indonesia, Malaysia, Thailand, Colombia, and Nigeria (Gonzalez-Diaz et al., 2021), with an output of 91 million tonnes in 2023 (USDA and FASUDA, 2023). India, Pakistan, and Bangladesh are the biggest importing regions (60 % of total imports), are accounting for around 17 Mt of the world's imports of palm oil, followed by the EU-27 with 6.5 Mt and China with 5 Mt (Murphy et al., 2021).

Palm oil production has risen steadily over the last several years and is anticipated to reach 240 million tonnes by 2050 (Azhar et al., 2017), as demand for palm oil uses involved in the manufacturing of food (e.g. margarine, cooking oil, bakery products, dairy products, fried and baked foods) and animal feed preparations as well as numerous non-food products (e.g. biodiesel, textiles, and cosmetics) grows (Gonzalez-Diaz et al., 2021). Although the oil palm sector has been appreciated for its role in economic development and prosperity of the producing countries, it has also been linked to negative environmental impact because of the enormous amounts of waste streams produced at both the input and output sides of the oil extraction operations.

Generally, there are two types of palm oil milling processes: dry and wet (typical). The latter process is mainly used by the majority of oil palm mills to extract the oil. After the fresh fruit bunches (FFB) are delivered to the palm oil mills, several unit operations are applied for the extraction of the palm oil. The derived streams are (i) crude palm oil, palm kernels (desired products); (ii) empty fruit bunches (EFB), palm-pressed mesocarp fibre (PPF), palm kernel shells (PKS) (product specific byproducts); and (iii) palm oil mill effluent (POME) and sludge (POMS) (process specific streams) (Liew et al., 2006; Liew et al., 2015; Poh et al., 2020; Tan, 2006).

POME has the highest amount among all wastes. About 50 % (approximately 0.7 m^3/tonne of FFB processed) of the water input end up as POME throughout the milling process, while the other 50 % is lost into drains or rivers, or through evaporation (Gonzalez-Diaz et al., 2021; Liew et al., 2006; Liew et al., 2015). The three main sources of POME in the oil palm production process are the clarification wastewater (around 60 % of the POME), the sterilizer condensate (around 36 % of the POME) and the hydrocyclone wastewater (around 4 % of the POME) (Liew et al., 2015; Mohammad et al., 2021; Poh et al., 2020). Based on literature data (Mohammad et al., 2021; Poh et al., 2020; Rupani et al., 2010; Sinnaraprasat and Fongsatitkul, 2011; Wong et al., 2021), POME is a viscous, colloidal suspension consisting mainly of water (95–96 %), total solids (4–5 %), suspended solids (2–4 %) made up of lignocellulosic debris from palm fruit mesocarp, oil (0.6–0.7 %), and a spectrum of carbohydrates from hemicelluloses to simple sugars, organic nitrogen (proteins, amino acids), and organic acids. It also contains important amounts of the plant nutrients, including N, P, K, Mg, Ca, and heavy metals (As, Cu, Co, Pb, Fe, Cd, Zn, Hg, and Ni). Moreover, POME is characterized by a dark brownish colour, acidic pH value (<5), high values of COD (15,000–100,000) and BOD (10,250–43,750), and high temperatures (80 to 90 °C). Carotenoids (8 mg/L), phenolic compounds (5800 mg/L), pectin (3400 mg/L), tannins, and lignin (4700 mg/L) contribute to the brownish colour of POME. Numerous factors, such as the crop season, FFB's level of maturity, the various treatment methods, the different FFB batches, and the factory system, all have an impact on the POME quality. In order to prevent the detrimental impacts of POME waste, regulations on minimum requirements for the discharge of POME into the environment or water bodies have been set.

A typical FFB has about 21 % crude palm oil and the remainder is made up of the EFB (~23 %), PPF (13.5–15 %), PKS (5.5–7 %), and palm kernel (6–7 %). Every tonne of crude palm oil produced generates 1.8 t of solid biomass waste (EFB, PPF, and PKS). EFB, a byproduct of the stripping procedure used to prepare palm oil, is the main source of the solid biomass waste. The FFB brunches are stripped of their individual fruitlets in a revolving drum before being transferred to the digester and away from the EFB. Another solid biomass waste from the palm oil mill is the PPF, which is created when nuts are taken out of the fibre. The latter stream is mainly composed of mesocarp fibre, a few shards of kernel shell, and shattered kernels. Following the extraction of crude palm oil, PPF typically contains 5–6 % of residual oil. Additionally, PKS, the shell fractions that remain after the nut is cracked to release the palm kernel, is created. The main processing steps in addition to the sources and quantities of input water, main products/byproducts, and wastewater generation from the processing of FFB (Liew et al., 2015).

Solid wastes are typically burned, with the ashes from EFB being utilized as fertilizer and the PKS and PPF being burned to generate heat and energy for mill operation. Other approaches to deal with these wastes include extracting cellulosic material from fibres, converting wastes into bio-oil or biochar by pyrolysis, and making part of these wastes into briquettes to help energy production in other industries. Although there is a benefit to recover valuable goods from solid waste, some of the methods are labour-intensive and expensive, which discourages application. The treatment of POME, which is typically done using a series of ponds, still is problematic, such as the emission of greenhouse gases into the environment, taking up a lot of space, and having low treatment efficiency with a lengthy retention time (Poh et al., 2020). Due to their capacity to speed up the decomposition of the organic material, fungi have been recommended as effective natural decomposition agents for palm oil mill wastes (e.g., composting) (Dominic and Baidurah, 2022; Mohammad et al., 2012; Rupani et al., 2010). In view of the fact that POME contains great amounts of carbohydrates, proteins, lipids, and minerals, its bioconversion into value-added products via biotechnological means has been proposed as an alternative approach of effluent treatment. In this direction, POME has been recognized as an excellent substrate for fungal growth and, in turn, its remediation and advanced valorisation. Many fungi such as *Trichoderma viride* and *Aspergillus oryzae* were found capable of reducing the waste strength of POME and producing fungal biomass suitable as a valuable source of protein for animal feed (Abdul Karim and Ahmad Kamil, 1989; Barker and Worgan, 1981). Another potentially interesting approach to advanced valorisation of POME is the production of fungal enzymes. For example, the use of *Aspergillus niger* and *Neurospora crassa* has been reported for the production of phytase via POME utilization as a low-cost raw material (Sugiharto, 2018). Also, the predominant fungi isolated from palm oil mill wastewater (POME) composts, namely *Aspergillus*, *Penicillium*, *Trichoderma*, and *Mucor* genera, demonstrated high lipase-producing abilities (Nwuche and Ogbonna, 2011). Another innovative approach is the exploitation of *Humicola insolens*, *Thermomyces lanuginosus* and *Rhizopus oryzae* for the production of enzymes (carboxymethylcellulase (815 U/mL), xylanase (1550 U/mL) and pectinase (930 U/mL)) and biopolymer (MW 17,700 Da) (Prasertsan and Binmaeil, 2018).

3.2. Fish industry wastewaters

Fish processing is a significant global economic activity. Processing of fish and related byproducts inevitably uses large quantities of water on average equal to 11 m^3 tonne of fish processed for washing of raw products, the production of canned fish, the manufacture of fishmeal, or sterilization steps (Cristóvão et al., 2014; Queiroz et al., 2013). As a result of such activities, the fish industry generates a substantial amount of solid waste and wastewater, which contains significant amounts of colloidal and particulate forms like fish residues, as well as various oil and fat residues and soluble nutrients. These factors awakened environmental concern around the world (Chowdhury et al., 2010). Therefore, discharge of fish industry wastes (FIW) directly without any treatment process decreases the concentration of dissolved oxygen in the receiving water environment, leads to eutrophication, toxicity in the receiving water environment; and adversely affects the growth and reproduction of living organisms in the aquatic environment. It is very important to design an appropriate industrial wastewater treatment facility according to the degree of contamination. Pre-treatment methods like screening, sedimentation, pH adjustment, flocculation, and flotation ensure the removal of colloidal materials, large particles, settleable, and suspended solids. After pretreatment, secondary treatment (biological treatment) is carried out to remove the remaining organic pollutants by aerobic, facultative, and anaerobic microorganisms (Tay et al., 2004). Conventional biological treatment methods for example activated sludge requires high energy inputs combined with O_2 supply and do not allow recycling of nutrients present in the wastewater. Efforts to control wastewaters and utilize them as recycling resources with high potential rather than as pollutants and to produce products with high value biotechnological products for economic, environmental, and social sustainability have been increasing worldwide in recent years (Gao et al., 2018; Queiroz et al., 2013; Riaño et al., 2011). Therefore, it is very important to know the characteristics of such wastewater coming from such as fish industry for revealing its potential for production of high value products (such as protein-rich biomass and enzymes) through several bioprocesses (Gassara et al., 2010; Sar et al., 2020a; Sar et al., 2021a). The amount of organic load of the waste and its characterization in terms of nitrogenous compounds, phosphates, fat, inorganic matter, salinity, pH, odour, colour, BOD, and COD properties and pathogen risks are important points to consider (Queiroz et al., 2013; Riaño et al., 2011; Sar et al., 2020a; Sar et al., 2021a). For example, while salt typically has a detrimental effect on microbial activity, moderate acclimation through proper adaptation or the utilization of halophilic microorganisms can enable thriving in high salinity environments (Aloui et al., 2009). The characteristic of the wastewater differs due to the processes applied but also depends on the type of raw fish (Table 1). Accordingly, under the scope of a biorefinery, FIW can be used to support the different microbial growth simultaneously converting the organic matter, nitrogen, and phosphorus of FIW into biomass that is favourable for energy and nutrient productions.

Table 1
Characteristics of fish processing wastewater (Queiroz et al., 2013; Riaño et al., 2011; Sar et al., 2020a; Sar et al., 2021a).

Parameters	Range of value
pH	6.7–8.0
Total COD (mg/L)	710–3720
Soluble COD (mg/L)	186–3260
Total nitrogen (N-TKN) (mg/L)	31–510
Ammonium (NH_4^+) (mg/L)	8–64
Total phosphorus (P-PO_4^{-3})	1.3–13.7
Total solids (TS) (mg/L)	591–17,140
Dissolved solids (DS) (mg/L)	231–16,190
Volatile solids (VS) (mg/L)	493–2930
Crude protein (g/L)	2.66–3
Salt	1–6 %
Crude fat (g/L)	5.69–7.15
Glucose (g/L)	0.013–0.021
Glycerol (g/L)	0.002–0.004
Lactic acid (g/L)	0.307–0.469
Acetic acid (g/L)	0.139–0.267
Ethanol (g/L)	0.007–0.017

3.3. Dairy wastes

The increasing demand for dairy products all over the world has enabled the dairy industry to develop, while at the same time leads to increased production of process wastewater. Dairy wastewater is categorized depending on its source, composition and process conditions; milk lost in technological cycles dairy products (skim milk, spoiled milk and spilled milk), byproducts of processing operations products (whey permeate, whey, boiling water, buttermilk, brine), clean-in-place (CIP) reagents, a wide range of cleaning acid, and alkaline detergents used in the washing of containers, cans, bottles, equipment tanks, and floors (Carvalho et al., 2013; Kolev Slavov, 2017; Sar et al., 2021b). Depending on the type of product, the quality of the water used, production technique, and control, the processing of 1 L of milk generates 6–10 L of wastewater. Every year, dairy waste, covering about 4–11 million tons worldwide, is released into the environment as a serious threat to biodiversity. The main liquid byproduct of the dairy industry is whey, which is produced during cheese and casein production (Britz et al., 2006; Kolev Slavov, 2017). Whey, characterized by its physicochemical properties such as minerals (0.46–10 %), total suspended solids (0.1–22 g/L), pH (3.3–9.0), phosphorus (0.006–0.5 g/L), total nitrogen (0.01–1.7 g/L), organic load (0.6–102 g/L), lactose (0.18–60 g/L), protein (1.4–33.5 g/L), and fats (0.08–10.58 g/L), constitutes the primary environmental impact for the dairy industry (Carvalho et al., 2013; Kolev Slavov, 2017). Buttermilk is another liquid byproduct coming from butter processing procedures rich in milk fat globule membrane (MFGM), phospholipid, and bioactive peptides (Avci and Özcan, 2020). Generally, dairy industry wastes (DIW) have high BOD (40–48,000 mg/L), COD (80–95,000 mg/L), and pH ranging from values of 4.7 to 11. The wide variability in pH values and content is influenced by factors such as the cleaning method employed, the concentration of different acid/alkaline detergents in cleaning water, and the extent of heating during milk processing. Additionally, variations can occur due to residues from other processing methods and the manner in which they are eliminated. DIW is usually white in colour (whey yellowish-green in colour), have an unpleasant odour and turbid character (Kolev Slavov, 2017; Shete and Shinkar, 2013). The treatment of DIW, especially whey, can be carried out using various physicochemical and biological methods. Physicochemical methods such as coagulation-flocculation, chemical precipitation, and advanced oxidation processes are commonly used. However, these methods are often associated with higher costs and limited effectiveness in removing soluble COD. In contrast, biological methods, including anaerobic digestion and aerobic biological digestion, are more cost-effective and efficient at reducing the organic load. These biological processes leverage microbial activity to break down organic pollutants, resulting in higher COD removal rates and overall better treatment efficiency.

Valuable microbial metabolites and biomass derived from industrial wastes are crucial due to their potential to produce new functional products and reduce environmental pollution. Examples of valuable metabolites include enzymes like amylases and proteases, organic acids such as citric acid and lactic acid, and bioactive compounds like antibiotics and vitamins (Chandra et al., 2018; Sar et al., 2021b). These metabolites can be used in various industries, including pharmaceuticals, food, and biofuels. For instance, the production of citric acid from industrial waste can significantly lower the environmental footprint compared to traditional manufacturing methods. Moreover, utilizing such biological wastes in biotechnological processes can reduce environmental pollution by decreasing the organic load and contaminants released into the ecosystem, potentially lowering pollution by up to 70 % as these wastes are converted into useful products rather than being disposed of untreated (Awasthi et al., 2022; Sar et al., 2021b).

3.4. Starch-based wastewaters

Food waste is produced in many different ways, including food processing plants, commercial and domestic kitchens, hotels, restaurants, and other areas of mass food production sectors. The wastes from starchy root crops like potato, cassava and sweet potato, as well as waste streams from the brewery and starch production industries, are burned or disposed of, causing environmental and human health problems. Nevertheless, these wastes could be a source of minerals, vitamins, or dietary fibre that could be transformed into low-cost medium supplements for culturing fungi or a value-added green product, including ethanol and methane.

Potato byproducts (potato peel waste (PPW)) are generally used as animal feed or thrown away causing environmental problems. The use of PPW for productions of lactic acid (298 mL/mg PPW) and ethanol (33 mL/mg PPW) by *Rhizopus oryzae* has been reported (Uyar and Uyar, 2023). The PPW was also found to be suitable substrate for *Scytalidium acidophilum* and *Rhizopus delemar* for production of single cell protein with a promising amino acid profile to be used as animal feed (Sar et al., 2022; Taskila et al., 2023). The amylase-producing *R. stolonifer* enhanced methane (biogas) production from potato peels by 24.95 % compared to unhydrolyzed potato peel wastes through the anaerobic digestion process (Almuhayawi et al., 2023). Additionally, *Monascus purpureus* (Went NRRL 1992) was able to produce pigment (29.86 AU/mL) using potato processing effluent and waste powder which was then employed as a natural colourant for ice lollies (Abdel-Raheam et al., 2022).

The improvement of biodegradability of high starch containing wastewater such as PPW by fungal treatments was investigated. It was shown that potato wastewater could be feasible substrate for bioflocculant production by isolate *Aspergillus niger* A18. After flocculation of potato waste water that outflow was recommended to be used for irrigation (Pu et al., 2018). Potato starch and potato wastewater were also used as promising co-substrates for decolourization of textile dyeing wastewater by *Penicillium chrysogenum* (Lanfranconi et al., 2022). Moreover, co-culturing of microalgae *Chlorella pyrenoidosa* and *A. oryzae* effectively treated potato waste water and produced high value biomass (Wang et al., 2022).

Sweet potato processing also generates a huge amount of waste that can be used for starch production. Sweet potato peel starch was converted to high level of glucose by α-amylase by using *A. niger* extract providing ethanol production in an economic manner (Pereira et al., 2017). Biosurfactant productions were achieved by *A. niger* and *Fusarium oxysporum* isolates grown on sweet potato peel broth with high oil dispersal area (Ezeonu and Otiwa, 2020). Fermentation of sweet potato peel showed that *A. niger* and *A. terreus* could produce itaconic acid as a rising organic acid for polymer industry (Omojasola and Adeniran, 2014). Recently, production of gluconic acid from sweet potato peels by using *A. niger*, *Penicillum* sp. and *A. terreus* strains was attained. It was reported that among the tested strains, *A. niger* UFMGCB 14248 and *A. niger* ATCC 10577 produced the highest levels of gluconic acid (Ajibo and Said, 2023).

The wastewater (including the suspended solids) of a wheat-starch plant was used as a substrate for the cultivation of *A. oryzae* and *R. oryzae* and protein rich biomass (12 g/L of dry biomass with protein content about 35 %) was obtained (Souza Filho et al., 2019).

The cassava starch processing (CSP) wastewater with nitrogen supplementation has also been investigated for improved production of biomass by *A. oryzae* IFO 30113 (Tung et al., 2004). The cassava peels were used as substrate for production of α-amylase by *A. flavus*, *A. niger*, and *P. expansum* (Aisien and Igbinosa, 2019). In addition, biodegradability of tapioca starch wastewater by fungi mixture composed of *Trichoderma*, *Aspergillus*, and *Candida* strains was evaluated. The COD removal (up to 90 %) and the fungal biomass with high protein content that can be consumed by human and animals were reported (Wonglertarak et al., 2021).

The starch containing pea processing byproduct has been shown to be a feasible substrate for the growth of edible strains of *A. oryzae*, *F. venenatum*, *M. purpureus*, *N. intermedia*, and *R. oryzae* for the production of vegan mycoprotein for human consumption (Souza Filho et al., 2018).

Organic kitchen wastes with high carbohydrate content can be utilized as culture media for microorganisms, including fungi such as *Trichoderma harzianum* as a biological pest control agent (Escalante et al., 2022). Additionally, biodegradation of kitchen waste was attained by fungi, including *T. harzianum*, *A. niger*, *A. flavus*, and *P. expansum* (Ashraf et al., 2017). The bread waste was also used to produce a protein and fatty acids rich fungal biomass using *R. delemar* (Svensson et al., 2021).

The nutritional profile of fungal biomass need be taken into consideration in order to determine its sustainability for human nutrition or in feed applications. The feasibility of a commercialization process should also be evaluated through techno-economic analysis and life cycle assessment of starchy waste valorisation by filamentous edible fungi.

3.5. Textile wastewater & dye industry

The global textile industry, revered for its wide range of colours and an assortment of fabric designs, plays an integral role in our everyday clothing requirements. While making a considerable contribution to the world economy, this industry concurrently produces vast quantities of wastewater, signalling serious environmental and public health concerns. The wastewater resulting from textile and dye processes is characterized by high levels of both COD and BOD, with a ratio of 4:1. This disproportionate ratio signifies the presence of compounds resistant to biodegradation, underscoring the complexities of dealing with such wastewater. In addition, the effluent contains substantial amounts of suspended solids and an array of harmful dyes, thereby exacerbating the ecological predicament. At present, >100,000 distinct types of dyes are commercially available, and they form a critical part of the textile manufacturing process. Their global production has escalated to a staggering 1 million tons, further magnifying the environmental burden (Gupta and Suhas., 2009; Yaseen and Scholz, 2019). This staggering volume of dye production and usage not only highlights the scale of the issue but also underscores the urgent need for effective treatment and management solutions to safeguard our environment and public health.

The textile manufacturing process is complex, entailing numerous stages and varying treatment methods, which can be broadly classified into two categories: wet and dry processes. The type of waste and discarded chemicals produced largely hinges on the kind of treatment employed.

In wet processing, a series of procedures take place, including pretreatment operations like sizing and de-sizing, scouring, bleaching, and mercerization, followed by dyeing and finishing stages. These processes lead to the generation of an extensive amount of contaminated wastewater (Yaseen and Scholz, 2019). Indeed, it is estimated that approximately 200 L of water may be consumed for every kilogram of finished textile produced, emphasizing the industry's high water footprint (Ghaly et al., 2014). In terms of dyeing, all fibres can generally be categorized into three main groups: cellulose fibres, typically dyed using reactive dyes, direct dyes, naphthol dyes, and indigo dyes; protein fibres, primarily dyed with acid dyes and lanaset dyes; and synthetic fibres, coloured using disperse dyes, basic dyes, and direct dyes (Table 2)

Table 2
Examples of specific dyes have been given (Ghaly et al., 2014).

Dye type	Example of dye
Reactive dyes	Remazol, procion MX and cibacron F
Direct dyes	Congo red, direct yellow 50 and direct brown 116
Naphthol dyes	Fast yellow GC, fast scarlet R and fast blue B
Indigo dyes	Indigo white, tyrian purple and indigo carmine
Acid dyes	Azo dyes, triarylmethane dyes and anthraquinone dyes
Lanaset dyes	Blue 5G and Bordeaux B
Dispersed dyes	Disperse yellow 218 and disperse navy 35
Basic dyes	Basic orange 37 and basic red 1

(Kehinde and Aziz, 2014). However, it is essential to recognize that the detailed composition and pH of textile wastewater can vary significantly. Several factors contribute to this variance, including the type of fabric being processed, the factory equipment used, the volume of fabric produced, country-specific regulations, and even seasonal and fashion trends (Table 3). This dynamic nature of the textile wastewater composition underscores the need for adaptable and comprehensive wastewater treatment solutions (Yaseen and Scholz, 2019).

Due to the vast diversity in processes, fibre types, and technologies employed in textile manufacturing, the resultant effluents present a complex mixture of contaminants. These can encompass dyes, metal ions, acids, bases, dissolved solids, suspended matter, oils, or surfactants (Premaratne et al., 2021). Among the contaminants, the presence of metal ions is particularly concerning. The primary metals frequently detected in textile wastewater include chromium, arsenic, copper, zinc, lead, iron, mercury, and cobalt (Hussein, 2013; Joshi and Santani, 2012; Manekar et al., 2014; Mani et al., 2019). Some of these metals, such as cobalt, copper, and chromium, are often integral to the dye chromophores, playing a significant role in conferring colour to the dyes (Velusamy et al., 2021). However, the concentration of these metals in textile wastewater can greatly vary, reflecting the influence of several factors such as geographical location and the specific technologies used in production. Therefore, a comprehensive understanding of the wastewater's composition is essential to devise effective and tailored wastewater treatment strategies. To provide a clearer perspective, Table 4 delineates several examples of the extent of metal contamination found in textile wastewater across different contexts. This serves to underscore the critical need for stringent measures to mitigate the environmental impact of this pervasive industry.

Fabric dyes, particularly synthetic ones, are recognized as one of the principal environmental challenges associated with textile production. These dyes, due to their synthetic nature and resistance to biodegradation, can cause significant environmental risks. Depending on their chemical structure, these dyes can be classified into various groups, such as azo, anthraquinone, sulphur, phthalocyanine, and triarylmethane. Alternatively, classification can also be based on their application type — for instance, reactive, direct, disperse, basic, and vat dying (Popli and Patel, 2015). Throughout the dyeing process, a part of these dyes does not adhere to the fabrics and therefore gets flushed away during the rinsing stages. It's estimated that about 20 % of the dyes used can be directly discharged into the environment or released during the dyeing processes. Studies have reported that dye concentrations in textile wastewater can span a broad range, generally varying from tens to several hundreds of milligrams per litre (Yaseen and Scholz, 2019). Beyond their toxicity, dyes can also interfere with the natural photosynthetic processes in contaminated ecosystems due to their sunlight adsorption and reflection properties can cause an undesirable environmental impact (Premaratne et al., 2021). This interference can potentially disrupt the food web's stability (Mani et al., 2019). In dye-containing wastewater, colour from dye pollution can be noticeable at as low as 1 mg/L, and instances of contamination as high as 300 mg/L have been reported (Kurade et al., 2015). In recent decades, decolourisation has emerged as a persistent challenge linked with the textile and dye wastewater industry. The chemical structure of fibre dyes, founded on aromatic rings, confers a high degree of persistence against biological degradation in wastewater treatment plants (WWTP). As a result, a comprehensive treatment strategy often necessitates both anaerobic and aerobic stages (Willetts and Ashbolt, 2000). This insight further underscores the need for innovative, efficient, and ecologically sound strategies to manage and treat dye-contaminated wastewater.

Table 3
The type of chemicals released in fibres processing is connected to the stage of treatment (Geethakarthi, 2021; Samanta et al., 2019).

Process	Used or released chemicals
Sizing	Starch cellulose derivatives, PVA, and polyacrylates
Desizing	Starch, waxes, and CMC
Scouring	Sodium hydroxide, surfactants, soaps, fats, pectin, oils, sizes, and waxes
Bleaching	Hydrogen peroxide, sodium silicate, organic stabilizer, and alkaline conditions
Mercersing	Strong caustic alkaline solution
Dyeing	Metals, salt, surfactants, colour and alkaline/acidic conditions, and soda ash
Printing	Colour, metals, urea, formaldehyde, solvents, and urea
Finishing	Softeners, solvents, resins and waxes, PVA, and hydrocarbons

Table 4
Value ranges of metals detected in textile wastewater.

Metal	Concentration (mg/L)	Reference
Cr	6.18	(Ghazal et al., 2018)
Al	8.6	(Brar et al., 2019)
As	3	(Ghazal et al., 2018)
As	<0.001	(Lim et al., 2010)
Cd	0.01–0.05	(Lim et al., 2010)
Cu	8.14	(Ghazal et al., 2018)
	3.65	(Brar et al., 2019)
	<0.001–0.1	(Lim et al., 2010)
Fe	95.2	(Ghazal et al., 2018)
	31.43	(Brar et al., 2019)
	0.11–0.16	(Lim et al., 2010)
Mn	0.01–0.04	(Lim et al., 2010)
Mo	2.6	(Ghazal et al., 2018)
Ni	0.02–0.04	(Lim et al., 2010)
Pb	10	(Ghazal et al., 2018)
	0.28	(Brar et al., 2019)
	0.08–0.09	(Lim et al., 2010)
Se	1.08	(Brar et al., 2019)
Sr	0.85	(Brar et al., 2019)
V	1.38	(Brar et al., 2019)
Zn	1.03	(Brar et al., 2019)
	0.11–2.93	(Lim et al., 2010)

In addition to the direct toxic effects caused by agents used in fibre processing, it's important to consider other sources of environmental contamination from the textile industry. Photochemical, physicochemical, and microbiological decomposition and metabolism of these agents can lead to the generation of additional pollutants, which can further exacerbate the impact on the ecosystem (Yaseen and Scholz, 2019). Another significant environmental issue associated with textile wastewater is the presence of phosphorus and nitrogen. The occurrence of these elements in textile wastewater has been reported to reach concentrations up to several thousand milligrams per litre (Brar et al., 2019; Lim et al., 2010; Logroño et al., 2017; Vijayakumar and Manoharan, 2012; Wu et al., 2017). The abundance of phosphorus and nitrogen in textile wastewater is particularly concerning, as these nutrients can promote eutrophication in aquatic ecosystems - a process that leads to excessive growth of plants and algae, which can significantly deplete the water's oxygen levels, leading to the death of other aquatic organisms. Therefore, it is essential that strategies for managing textile wastewater consider these aspects to ensure comprehensive treatment and mitigation of environmental harm.

Some studies have demonstrated the effectiveness of white rot fungal species capable of synthesizing manganese peroxidase (MnP), lignin peroxidase (LiP), and laccase enzymes in purifying textile wastes contaminated with dyestuffs (Asgher et al., 2009; Juárez-Hernández et al., 2021). *Dichomitus squalens*, *Daedalea flavida*, *Irpex flavus*, *Polyporus sanguineus*, *Coriolus versicolor*, *Phanerochaete chrysosoporium* and *Bjerkandera adusta*, *Emmia latemargina* and *Talaromyces verruculosus* have been intensively studied for the decolourization of dyes (Chadni et al., 2017; Jarosz-Wilkołazka et al., 2002; Juárez-Hernández et al., 2021; Liu et al., 2004). On the other hand, some filamentous fungi (*Aspergillus quadrilineatus*, *A. terreus*, *A. lentulus*, *A. carbonarius*, *Chaetomium globosum* and *Penicillium glabrum*) have also been found to be effective in colour removal (Arikan et al., 2019; Kaushik and Malik, 2010; Manai et al., 2016; Singh and Dwivedi, 2020; Yusuf et al., 2023). Bernal et al. (2021) reported that *Sarocladium* sp ITF33 isolated from textile wastewater had specific collagenolytic activity, and enzymes and secondary metabolites of these types of isolated microorganisms had potential in medical and pharmaceutical fields.

3.6. Pharmaceutical wastes

The occurrence of pharmaceuticals in wastewater, and consequently in the natural environment, is linked to human activity. Given the extensive diversity in pharmaceutical chemicals - in terms of their origin, mechanisms of action, and resilience to (bio)degradation - predicting their potential impact on both target and non-target organisms poses a significant challenge. Several pharmaceutical xenobiotics are frequently detected in wastewaters and the environment, including endocrine disruptors, hormones, non-steroidal anti-inflammatory drugs (NSAIDs), antimicrobial agents, pharmaceuticals and personal care products (PPCPs), beta-blockers, and lipid-regulating agents (Dong et al., 2023; Khan et al., 2020; Marchlewicz et al., 2023; Rezaei et al., 2022; Shojaee Nasirabadi et al., 2016; Winker et al., 2008). These compounds, often derived from artificial modifications of natural substances or entirely synthetic in origin, demonstrate a notable resistance to biological treatment in WWTP. Consequently, this resilience heightens the challenge of efficiently removing these pollutants during conventional wastewater treatment processes (Marchlewicz et al., 2017). On the other hand, photodegradation and advanced oxidation processes (AOPs) appear to show promise in the degradation of these stubborn xenobiotics. However, these processes often give rise to unpredictable metabolites. This consequence further complicates the management of pharmaceutical contaminants in wastewater and emphasizes the need for more comprehensive and advanced treatment strategies to safeguard environmental health (DellaGreca et al., 2003; Górny et al., 2019).

Pharmaceutical compounds, rather than being degraded or decomposed within organisms, typically undergo two distinct detoxification phases. These processes transform them into more polar and water-soluble forms, thereby facilitating their elimination via urine. In the first phase, pharmaceuticals are subjected to oxidation, reduction, or hydrolysis, primarily catalysed by the enzyme system NADPH-cytochrome P450 reductase (P450R)/cytochrome P450 (P450). The second phase encompasses conjugation reactions mediated by UDP-glucuronosyltransferases, which further enhance the compounds' water solubility and consequent excretion (Iyanagi, 2007). Following excretion, these pharmaceuticals and their metabolites enter WWTPs, where a portion undergoes further metabolism or partial degradation. However, due to characteristics such as high polarity, volatility, lipophilicity, persistence, and a propensity for adsorption, many pharmaceutical compounds are not efficiently removed during conventional wastewater treatment processes (Khasawneh and Palaniandy, 2021; Majumder et al., 2019). This inefficient removal can lead to the detection of pharmaceutical residues not only in raw sewage but also in treated wastewater and the wider environment. Moreover, in many cases, the metabolites of these pharmaceuticals can exhibit higher toxicity levels than the parent compounds due to increased solubility and bioavailability. Oxidized metabolites and their conjugates are among the most common metabolites found in wastewaters and the environment. For instance, metabolites of NSAIDs such as ibuprofen, including 2-hydroxyibuprofen, carboxyibuprofen, 1-hydroxyibuprofen, and ibuprofen glucuronide (Marchlewicz et al., 2017). Similarly, naproxen metabolizes into *O*-desmethylnaproxen and its glucuronide conjugates (Wojcieszyńska and Guzik, 2020), and diclofenac transforms into 4′- and 5′-hydroxylated derivatives and its glucuronides (Wojcieszyńska et al., 2023). Carbamazepine, a common pharmaceutical contaminant, is frequently detected as metabolites such as carbamazepine-10,11-epoxide or 10,11-dihydro-10-hydroxy carbamazepine in wastewaters (Gurke et al., 2015). Similarly, *N*-desmethyl tramadol is a commonly detected metabolite of tramadol (Kharel et al., 2021). The presence and impact of these diverse pharmaceutical metabolites emphasize the necessity for more sophisticated and robust wastewater treatment strategies.

Typically, pharmaceutical residues in water bodies and rivers are found in the range of nanograms to micrograms per litre (ng–μg/L). However, their concentration in wastewater can be significantly higher, reaching levels up to several milligrams per litre (mg/L) (Khasawneh and Palaniandy, 2021). A noteworthy aspect is that for many pharmaceuticals, their metabolites can remain biologically active, thereby continuing to exert influence on the environment and organisms. For instance, the antibiotic erythromycin generates a biologically active metabolite, *N*-desmethyl-erythromycin (Monetti et al., 2022). Similarly, the beta-blocker propranolol produces a principal active metabolite, 4-hydroxypropranolol (Winker et al., 2008). Many of these metabolites are excreted as conjugates. However, bonds such as the glycosidic bond present in these metabolites can be easily hydrolysed by environmental microorganisms, releasing the active metabolite into the environment (Díaz-Cruz and Barceló, 2006). For example, the lipid-regulating agent gemfibrozil generates 5-(2-methyl-5-carboxyphenoxy)-2,2-dimethylpentanoic acid as a major metabolite. Indomethacin, an NSAID, produces several metabolites, including desmethyl indomethacin, deschlorobenzoyl indomethacin, desmethyldeschlorobenzoyl indomethacin and their glucuronides. Moreover, the antibacterial agent clarithromycin forms an active metabolite known as 14-hydroxy-6-O-clarythromycin (Winker et al., 2008). Given the potential environmental and health implications of these active metabolites, their effective management in wastewater treatment processes remains a critical area of concern and research.

In Table 5, several examples of specific pharmaceuticals in wastewater (WWTP influents) have been shown. Pharmaceuticals are intentionally designed as biologically active compounds with the primary objective of exerting therapeutic effects at the lowest possible doses (Citkowska et al., 2019; Lawson et al., 2021). Because of that, some pharmaceuticals can potentially impact various organisms, making their presence in environmental matrices a concern. An extra layer of complexity arises from the potential chronic effects resulting from long-term, low-dose exposure to these pharmaceuticals. While the acute effects of these drugs on their target organisms are often well-studied and understood, the same cannot be said for non-target organisms. The implications of pharmaceutical exposure on these organisms, particularly over a multi-generational timescale, remain largely unexplored. This is further complicated by the varied metabolic pathways these pharmaceuticals can take within different organisms, leading to a wide range of possible biological responses (DellaGreca et al., 2003; Górny et al., 2019; Liu et al., 2019; Świacka et al., 2021). Moreover, the different mechanisms through which these pharmaceuticals interact with non-target organisms are often not as well-defined or predictable as with their intended targets (Kwak et al., 2018; Näslund et al., 2020; Nunes et al., 2020). This scenario underlines the pressing need for further scientific investigation into the mechanisms of action of pharmaceuticals on non-target organisms, especially considering chronic, multi-generational exposures. Such studies are crucial in helping to build a more comprehensive understanding of the potential ecological and health risks associated with pharmaceuticals in the environment.

The purification of pharmaceutical substances through the utilization of white rot fungi (WRF) and their oxidoreductase enzymes has been suggested as a cost-effective and environmentally friendly solution (Naghdi et al., 2018; Olicón-Hernández et al., 2017a). Vasiliadou et al. (2016) reported that *Trametes versicolor* and *Ganoderma lucidum* totally degraded diclofenac, gemfibrozil, ibuprofen, progesterone and ranitidine. Additionally, it has been reported that the removal rates of some compounds that are difficult to degrade were increased by the co-culture of these two fungi (Vasiliadou et al., 2016). In the removal of xenobiotics, fungi from the Mucoromycota (formerly Zygomycota) group are often preferred (Dzurendova et al., 2022; Esterhuizen-Londt et al., 2016;

Table 5
Pharmaceuticals that can be found in wastewater and their value ranges.

Pharmaceutic	Group	Concentration μg/L	Reference
Valsartan	Angiotensin receptor blockers	0.1203	(Huang et al., 2018)
		29.7	(Gurke et al., 2015)
Sulfamethoxazole	Antibiotic	1.860 to 2.146	(Phonsiri et al., 2019)
		1.86–2.146	(Phonsiri et al., 2019)
Erythromycin		0.0167 to 0.278	(Phonsiri et al., 2019)
Triclosan		0 to 0.410	(Phonsiri et al., 2019)
Trimethoprim		0.407 to 1.021	(Phonsiri et al., 2019)
Tetracycline		0.206–0.225	(Al-Maadheed et al., 2019)
Gabapentin	Anticonvulsant	6.442–16.608	(Gurke et al., 2015)
		4.825–15.3588	(Tran and Gin, 2017)
Metformin	Antidiabetic	3.818–16.790	(Kot-Wasik et al., 2016)
Metoprolol	Beta-blocker	0.1646	(Huang et al., 2018)
Atenolol		3.56–26.5	(Thiebault et al., 2017)
Propranolol		0.00299–0.0975	(Subedi and Kannan, 2015)
Atorvastatin	Cholesterol lowering statin	0.070–0.75	(Golovko et al., 2014)
Estrone (E1)	Hormones	0.05–0.091	(Amin et al., 2018)
Estradiol (E2)		0.05–0.091	(Amin et al., 2018)
		0.0882–0.0939	(Yien Fang et al., 2019)
Clofibric acid	Lipid regulators	0.0175–0.0479 n.d.–0.0518	(Yan et al., 2014) (Papageorgiou et al., 2016)
Gemfibrozil		1.28–9.73	(Afonso-Olivares et al., 2017)
Acetaminophen	Nonsteroidal anti-inflammatory drugs	14.6	(Ramírez-Morales et al., 2020)
Ibuprofen		16.10–28.0	(Afonso-Olivares et al., 2017)
		16.433–96.519	(D'Alessio et al., 2018)
Ketoprofen		1.2254–4.0304	(Kot-Wasik et al., 2016)
Diclofenac		1.038–1.766	(Palli et al., 2019)
Tramadol	Opiate drugs	1.35–9.86	(Thiebault et al., 2017)
Caffeine	Stimulant	69.9	(Ramírez-Morales et al., 2020)

Olicón-Hernández et al., 2017a). Moreover, some filamentous fungal species from Ascomycota (*Fusarium* and *Trichoderma*) and Mucoromycota (*Umbelopsis ramanniana* and *Mucor rammanianus*) have potential to significantly degrade the pharmaceutical compounds such as carbamazepine, fluoroquinolones acetaminophen (Esterhuizen et al., 2021; Madadi and Bester, 2021; Olicón-Hernández et al., 2017a).

3.7. Paper-pulp industry

In the pulp and paper industry, wastewater production is a significant concern due to the high volume of water utilized in the manufacturing process. According to a 2022 report by the International Energy Agency (IEA, 2023), the annual global production of paper and pulp was 415 million tonnes, marking the highest production level since 2010. The water usage in the manufacturing process can vary significantly, ranging from 5 to 100 m^3/ton of paper and pulp. This variance is dependent on multiple factors, including the type of substrate used, the technology implemented, and the nature of the final paper product. On average, water consumption in paper mills typically falls between 10 and 50 $m^{3/}$ton (Sharma et al., 2022; Toczyłowska-Mamińska, 2017).

The timber processing in paper mills involves multiple stages, including debarking, chopping, pulping, bleaching, washing, filtering, screening, and either pulp drying or paper-making (Kamali et al., 2016). Consequently, these processes lead to the production of wastewater containing >500 different chemical compounds, primarily originating from the bleaching stage due to the degradation of lignin. Chlorinated compounds are of particular concern due to their usage of chlorine dioxide in the bleaching process (Khan et al., 2011; María Noel, 2017). The effluents contain a broad spectrum of contaminants, such as lignin, stilbenes, phenols, dioxins, chlorides, furans, and sulphur compounds (Ali and Sreekrishnan, 2001; Karrasch et al., 2006).

These effluents also present high values for COD and BOD, indicating a significant organic load. Furthermore, the pH of the wastewater can range broadly between 2 and 12, depending on the specific process stage (Ekstrand et al., 2013; Sharma et al., 2022). In some instances, heavy metals have also been identified as part of the contaminants (Hassan et al., 2014). In the chemical pulping process, high-pressure and high-temperature conditions are utilized, along with an array of different chemicals. In the Kraft process, for example, sodium hydroxide and sodium sulphide are used to cook woodchips in a pulping liquor to produce white liquor. Alternatively, other processes employ acidic treatments with sulphurous acid and bisulfide ions. Other inorganic compounds, such as sodium carbonate, sodium bicarbonate, sodium sulphate, sodium sulfite, or sodium thiosulfate, may also be added, resulting in green liquor. This can be converted into white liquor through further processing steps (Gopal et al., 2019; Kamali et al., 2016; Morya et al., 2022). Mechanical processing methods offer a higher yield of 90–95 % compared to the 40–50 % yield from chemical processes. However, mechanical processes tend to produce pulp of lower quality, with shorter fibres and higher colour intensity. Hence, despite the higher yield, chemical treatment is often preferred due to its superior output quality (Pokhrel and Viraraghavan, 2004).

Lignin, a component that imparts a dark colour to intermediate products, is not entirely removed from the processed material. This, along with lignin degradation products and cellulose content, contributes to the dark colour of mill effluent, commonly known as "black liquor". Approximately seven tonnes of this byproduct can be generated during the production of one tonne of paper pulp (Morya et al., 2022). The high organic matter content in black liquor can make it a viable substrate for alternative uses such as the production of hydrogen, biogas, bioplastics, biodiesel, and other valuable products (Boonyarit et al., 2020; Gao et al., 2014; Jiang et al., 2012; Morya et al., 2022; Srivastava et al., 2023; Yustinah et al., 2019).

The effluents from timber shredding and primary processing predominantly consist of tannins, lignin, hemicelluloses, and naturally occurring wood resins (Ali and Sreekrishnan, 2001; Avşar and Demirer, 2008; Vepsäläinen et al., 2011). Moreover, chemical pulping and bleaching operations produce an array of waste chemicals, including residual wood shreds, bark particles, colour, resin acids, fatty acids, dissolved inorganics, as well as lignin, and hemicelluloses. Trace chemicals such as soluble silicates and a range of compounds post-bleaching like chlorophenols, adsorbable organic halogens, extractable organic halogens, polychlorinated biphenyls, dioxins, furans, and chlorinated resin acids are also present (Betancur et al., 2009; Ekstrand et al., 2013; Huuha et al., 2010; Kansal et al., 2008; Koistinen et al., 1994; Requejo et al., 2012; Sainlez and Heyen, 2013; Uğurlu and Karaoğlu, 2009; Vepsäläinen et al., 2011).

The diverse array of technologies, legislative constraints, and processing methodologies applied within the paper production industry give rise to a wide spectrum of pollutant concentrations in wastewaters.

This vast variation makes it difficult to establish a standard comparison or generalization across the board. Wastewater pollutant content can differ significantly based on the source of the wastewater, the timing of the sample collection, and the geographical location of the production site. For instance, the concentration of lignin, an organic polymer derived from wood, can fluctuate dramatically from a few hundred milligrams per litre to several thousand milligrams per litre (Uğurlu and Karaoğlu, 2009; Zainith et al., 2019). A similar situation can be observed with other potential contaminants such as phenolic compounds, which can range in concentration from several micrograms to several grams per litre in the effluent (Chandra et al., 2009; Singh et al., 2008; Uğurlu and Karaoğlu, 2009). Likewise, organic acids, such as acetic acid or resin acids, also display a broad range of concentrations in the wastewater, complicating their tracking and treatment (Toczyłowska-Mamińska, 2017).

These substantial variations underscore the necessity for individualized assessments of wastewater pollutants and the development of site-specific treatment strategies. Furthermore, they highlight the need for ongoing research and continuous monitoring to accurately identify and manage the diverse range of contaminants that may be present in the wastewater produced by the pulp and paper industry. Paper recycling, while requiring a lower volume of water than the original manufacturing process, still demands the addition of certain chemical additives for de-staining. These include sodium hydroxide, hydrogen peroxide, surfactants, silicates, and carbonates (Ashrafi et al., 2015; Guedez and Püttmann, 2014; Hassan et al., 2014; Zhenying et al., 2009). Therefore, it's crucial to develop and implement effective strategies for treating the wastewater generated in these processes to mitigate their environmental impacts.

Extracellular fungal enzymes, including laccase, lignin peroxidase, and manganese peroxidase, which actively participate in the degradation of various pollutants, also exhibit the capability to degrade wastewater from the paper and pulp industry (Rajwar et al., 2017). *Pleurotusostreatus*, *Phanerochaete chrysosporium*, *Lentinus edodes*, *Trametes versicolor*, *Magnaporthe grisea*, *Mauginella* sp., *Paraconiothyrium variabile*, and *Monocillium indicum* are potentially evaluated to degrade paper mill effluents (Gupta et al., 2022; Rajwar et al., 2017).

Spent sulfite liquor (SSL) from pulp mill is a lignocellulosic waste containing sugars (mainly hemicelluloses-derived sugars), lignosulfonates and other organic compounds (Asadollahzadeh et al., 2017a). Different types of filamentous fungi, namely *Aspergillus oryzae*, *Rhizopus oryzae*, and *Mucor indicus*, can be grown on SSL to produce protein-rich fungal biomass and ethanol (Asadollahzadeh et al., 2017a; Asadollahzadeh et al., 2018; Asadollahzadeh et al., 2017b; Taherzadeh et al., 2003). SSL is also a valuable feedstock for the production of important enzymes such as xylanase and cellulase by fungi such as *Penicillium decuraben*, *Aspergillus phoenicis*, *A. oryzae*, and *A. foetidus* (Chipeta et al., 2005; Yinbo et al., 1991).

3.8. Wastewaters containing pesticide

Pesticides play a crucial role in global agricultural production, ensuring higher crop yields from limited areas, an aspect vital for sustainable food production and management, particularly given the increasing global population (Münze et al., 2017). Undesirably, pesticide residues often permeate far beyond their intended application areas, infiltrating various ecosystems through atmospheric, overland, subsurface, and groundwater pathways. The primary source of pesticide influx into sewage systems can be traced back to agricultural activities such as field sprayer filling and cleaning operations on impervious surfaces, the discarding of unused product residues, and inadvertent spillages (Münze et al., 2017). However, non-agricultural uses also contribute substantially to the burden of pesticides in sewage systems. These sources include turf management practices (like in golf courses and parks), industrial vegetation control (along highways and railroads), and pest control measures employed in residential homes and gardens (Münze et al., 2017; Saleh et al., 2020). Pesticide contamination presents a considerable challenge, especially when considering the use of fungi species for wastewater treatment. For instance, Münze et al. (2017) identified 45 different pesticides in effluents discharged from German WWTPs, which were classified into 19 herbicides, 14 fungicides, 7 insecticides, and 5 other metabolites. This pattern of pesticide pollution is commonplace, with numerous studies documenting a wide array of pesticides present at concentrations in the nanogram per litre range (Campos-Mañas et al., 2017; Haddaoui et al., 2016; K'Oreje et al., 2018; Köck-Schulmeyer et al., 2013; Manoli et al., 2019). Despite these low concentrations, the potential risk to organisms from chronic exposure to mixtures of these compounds cannot be underestimated (Trellu et al., 2021). For instance, chronic exposure to the herbicide atrazine, a selective photosynthesis inhibitor, has been linked to human cardiovascular issues, retinal degeneration, muscle deterioration, and cancer. Similarly, oxyfluorfen, another herbicide that inflicts irreversible cell membrane damage, can lead to liver disorders and anaemia in humans upon exposure (Saleh et al., 2020).

The treatment of pesticide-contaminated water presents an array of challenges, from the diverse composition of the influent and the variance in the physical structures of pesticides to the wide pH range of pesticide-polluted water, which can span from extremely acidic (0.5) to highly alkaline (14). Furthermore, the COD of pesticide-laden wastewater can fluctuate between 150 and 33,750 mg/L, while the BOD can vary between 30 and 11,590 mg/L. The levels of pesticides in different water sources can even reach up to 107 mg/L (Goodwin et al., 2017; Rodriguez-Narvaez et al., 2017). It's worth noting that current WWTPs are not sufficiently effective at eliminating pesticides from wastewater. Consequently, these harmful compounds are frequently found in environmental ecosystems, posing a significant threat to both ecological and human health (Münze et al., 2017; Rousis et al., 2017; Westlund and Yargeau, 2017). This situation underscores the urgent need for improved wastewater treatment techniques and strategies, particularly those capable of effectively removing pesticide residues.

3.9. Other industrial wastes

The global fruit and vegetable processing industry (canned/frozen fruits and vegetables, processed fruit and vegetable products such as vinegar/wine/sauce and fruit juices) is growing rapidly due to population growth and improvements in their production processes. Process wastewater from food, beverage and raw material facilities are also potential sources of environmental pollutants (Hubbard et al., 2022). Especially the high phenolic compounds and organic acid contents of fruit wastewaters and their high COD contents make their treatment important. (Chen et al., 2019; Strong and Burgess, 2008; Viuda-Martos et al., 2011). Filamentous fungi can be grown on winery wastewater, agro-industrial wastewater related to processing of fruits such as grapes, citrus and pomegranates which contain high phenolic content (Braho et al., 2023; Satari et al., 2016; Zhang et al., 2008). Fruit waste can also be considered as a potential substrate for pectinase enzyme production (Dhillon et al., 2004; Kc et al., 2020).

Sugarcane distillery spent wash water (DSW) is also an important industrial pollutant wastewater containing high COD level. Chuppa-Tostain et al. (2020) reported that species belonging to the *Aspergillus* and *Trametes* genera gave the best results in the purification of DSW. On the other hand, vinasse, a by-product of molasses-to-ethanol process, is also momentous wastewater containing high amounts of solids and COD (Nair and Taherzadeh, 2016). Research studies have shown that the edible filamentous fungi *Aspergillus oryzae*, *Rhizopus oligosporus* and *Neurospora intermedia* can grow on diluted vinasse and make a significant contribution to COD removal (Karimi et al., 2019; Nair and Taherzadeh, 2016; Nitayavardhana et al., 2013). Hashemi et al. (2021) proposed a two-step cultivation method for the valorization of vinasse, including fungal biomass production with *Neurospora* in the primary fermentation and further biogas production with anaerobic digestion.

4. Challenges on fungal biorefinery to treatment of wastewater

To ensure the effective treatment of wastewater by the fungal biorefinery, it is crucial to maintain the presence of fungal species within the system and optimize the production efficiency of existing fungi. Consequently, environmental factors, including temperature and pH, along with the composition of the wastewater employed, play vital roles in sustaining fungal production (Sankaran et al., 2010). Any alterations in the wastewater composition or the presence of inhibitors, such as acetic acid and furfural released during wastewater hydrolysis, can adversely impact fungal growth (Szengyel and Zacchi, 2000; Xiros et al., 2011). Hence, establishing optimal conditions for fungal cultivation in the wastewater intended for use in the treatment plant and conducting regular monitoring of wastewater parameters is essential (Assress et al., 2019; Badia-Fabregat et al., 2017).

Furthermore, the occurrence of contamination or genetic instability within the existing fungal population in the system can have detrimental effects on wastewater hydrolysis, fungal production, and consequently, the overall product yield (Jenkins and Grzywacz, 2000). Additionally, within the system, fungi may engage in competitive interactions. Although this competition can have a positive impact on fungal growth and product yield (Sperandio and Ferreira Filho, 2019), certain fungi may become more dominant, leading to alterations in product yield (Jenkins and Grzywacz, 2000). Hence, maintaining long-term stability of fungi within the system and implementing regular monitoring and control of the fungal population are imperative for consistent performance (Kumar et al., 2021).

The optimal parameters identified in a laboratory-scale may make a difference in large-scale reactor, where reactors may prove unsuitable for efficient fungus and bioproduct production (Dey et al., 2022). Therefore, the design of reactors for wastewater treatment requires the development of specialized processes and optimization techniques tailored specifically for fungal production (Dey et al., 2022; Espinosa-Ortiz et al., 2016). Challenges also arise in the form of mass and heat transfer within high-volume reactors (Modenbach and Nokes, 2012), which can significantly impact fungal biomass (Pallín et al., 2022). Moreover, even under optimal conditions, fungal production and alterations in wastewater composition can disrupt the pH balance of the environment, potentially hindering fungal growth. Hence, it is crucial to account for variables influencing fungal growth in the design of reactors. This holistic approach ensures that the challenges posed by scale-up, mass and heat transfer, and pH fluctuations are adequately addressed for successful fungal biorefinery processes in wastewater treatment.

In addition to the aforementioned challenges, achieving success in wastewater treatment and product extraction is not solely sufficient; it is imperative to ensure economic viability in terms of fungal biomass productivity and product yield (Chatterjee and Venkata Mohan, 2022). Furthermore, the acceptance and perception of the fungal species employed in wastewater treatment may pose challenges, requiring attention to public concerns. For the widespread adoption of fungal biorefinery approaches, addressing issues related to safety and potential environmental impacts is essential (Ferreira et al., 2020). Thus, a comprehensive approach that not only addresses technical challenges but also considers economic feasibility and societal considerations is vital for the successful implementation and acceptance of fungal biorefinery practices.

5. Regulatory and societal implications of wastewater-recovered biomass for food and feed

Resource recovery from wastewaters using filamentous fungi presents a promising approach for sustainable food and feed production. In terms of nutrient recycling, filamentous fungi are efficient at assimilating nutrients like nitrogen and phosphorus from wastewater, which are essential for their growth. This nutrient recycling can lead to the production of fungal biomass rich in proteins and other nutrients (Rousta, 2023). Filamentous fungi have bioconversion capabilities which enable them to convert low-value organic matter in wastewater into high-value proteins, carbohydrates, and byproducts, effectively turning waste into a resource (Negi and Das, 2023; Sankaran et al., 2010). Using these microorganism in resource recovery from wastewater can thereby contribute to sustainable development in that the approach aligns with circular economy principles, reducing waste and the need for new resources (Sankaran et al., 2010). In addition, beyond food and feed, this process contributes to bioremediation and mediating environmental challenges of wastewater as well as food and feed production (Parchami et al., 2021).

It is, however, noteworthy that there are challenges and considerations associated with using filamentous fungi in resource recovery from wastewaters. Relating to contaminant removal, it is important to consider that wastewaters often contain harmful pollutants. Ensuring that these are adequately removed or that they do not accumulate in the fungal biomass is crucial for safety (Hashemi et al., 2021). Further, regulatory compliance is crucial. Food and feed derived from wastewater-cultivated fungi must meet stringent safety and quality standards (Awasthi et al., 2023). In terms of public perception, recent research efforts have shown that people in Sweden and other parts of Europe positively perceive fungi-based food in the production of which resources that would otherwise go to waste (Hellwig, 2023). Nonetheless, acceptance of products derived from wastewater or other recovered resources requires significant public education and reassurance of safety (Hellwig et al., 2023; Hellwig et al., 2022).

The biomass derived from cultivating filamentous fungi on wastewater can have numerous applications in food and feed. This is due, not least, to the high protein content of filamentous fungi, making fungal biomass suitable for animal feed and potentially for human consumption, especially in alternative protein products (Hellwig et al., 2020; Rousta et al., 2021). Yet biomass from filamentous fungi and extracts thereof can also be used as functional ingredients in various food and feed products (Rousta et al., 2023).

Further research is necessary to develop the use of filamentous fungi in the recovery of resources in wastewaters. For example, identifying and optimizing fungal strains that have high growth rates and nutrient uptake efficiencies in different types of wastewater is vital (Awasthi et al., 2023). In terms of processing techniques it is important to develop methods to process fungal biomass into palatable, by the wider public desired, and nutritious forms of food and feed (Hellwig, 2023). To evaluate the social and environmental impacts and economic viability of cultivating filamentous fungi on wastewaters in the production of food and feed, it is also essential to conduct lifecycle assessment studies (Brancoli et al., 2021).

The recent surge of innovative approaches that utilize fungal biotechnology, especially in wastewater treatment, has led to a rise in intellectual property activities, particularly patents, with China leading in patents for using fungi in a diverse range of applications (Hüttner et al., 2020). Securing patents for these organisms, however, can be challenging in terms of detailed biological disclosure and complex legislation, even though international agreements like the Budapest Treaty aim to simplify this (Hüttner et al., 2020).

Using filamentous fungi for resource recovery from wastewaters offers a novel solution to waste management and sustainable food/feed production. While there are challenges, especially in safety, regulatory compliance, and public acceptance, the potential benefits in terms of sustainability, nutrient recycling, and environmental protection are significant. Ongoing research and development are critical to address these challenges and harness the full potential of this innovative approach.

6. Challenges and innovations in fungi from wastewater

Conventional biological wastewater treatment produces substantial quantities of low-value bacterial biomass, with the treatment and disposal of this bacterial biomass accounting for approximately 40–60 % of the wastewater treatment plant operating costs (Sankaran et al., 2010). Filamentous fungi offer a cost-effective alternative for biomass purification compared to bacteria in wastewater treatment processes. These fungi encompass numerous genera, including *Aspergillus*, *Penicillium*, *Fusarium*, *Verticillium*, *Pleurotus*, *Phanerochaete*, *Fomes*, *Agaricus*, *Ganoderma*, and *Phlebia* (Ghosh et al., 2023; Navina et al., 2024; Olicón-Hernández et al., 2017b) extensively studied for their bioremediation potential.

Among these genera, *Aspergillus* stands out for its broad application in remediating various environmental pollutants due to its diverse species and ecological roles. *Aspergillus* produces unique enzymes that are uncommon in other microorganisms, crucial for neutralizing toxic substances and bioremediating pollutants (Ghosh et al., 2023). It is known that the azo dye of white rot fungi is very effective in decolorizing. Species capable of metabolizing a wide range of xenobiotic compounds in this class, such as *Phanerochaete chrysosporium*, and alternatively various *Aspergillus* species have been reported to decolorize a variety of dyes (Alaguprathana et al., 2022; Ameen et al., 2021; Corso and Maganha de Almeida, 2009; Hamdi et al., 2022; Karatay et al., 2023; Sheam et al., 2021).

Optimal conditions for *Aspergillus* bioremediation include slightly acidic environments (pH 5–6), emphasizing the need for tailored bioremediation strategies (Singh, 2006). *Penicillium* strains, thriving in saline environments, possess advantages in bioremediation, with some acting as natural biosorbents for reducing heavy metal contamination (Ghosh et al., 2023; Leitão, 2009). Additionally, certain *Penicillium* species exhibit antimicrobial properties, improving the quality of treated wastewater by reducing pathogenic microorganisms (Robles et al., 2000).

Combining wastewater treatment with resource recovery through fungal bioremediation shows potential for economically viable and sustainable waste management (Sankaran et al., 2010). Recent advancements in metal biorecovery and bioremediation underscore filamentous fungi's eco-friendliness and effectiveness for industrial-scale operations, although challenges like optimizing metal recovery technologies and developing methods for metal removal post-bioaccumulation/biosorption remain (Ghosh et al., 2023).

Research on nutrient requirements for fungi in harvesting and treating wastewater is currently limited to specific types of wastewater. Therefore, there is a need to develop fungi-based processes that meet economic and regulatory requirements to establish a viable solution for creating a full-scale fungal wastewater treatment process aimed at resource recovery (Sankaran et al., 2010). Despite that, Beltrán-Flores et al. (2022) reported that employing suitable substrates, purification systems, and operational conditions enabled fungal technology to be implemented successfully under non-sterile conditions for long-term operations, thereby preparing it for full-scale applications.

In conclusion, while the current use of filamentous fungi in wastewater treatment shows promise, several areas necessitate further research. This includes optimizing environmental conditions, integrating fungal treatment systems into existing infrastructures, and assessing the acceptability of new systems. Comparative analysis of existing studies is crucial for gaining a better understanding of the factors influencing fungal activity, thereby guiding future research towards more efficient and sustainable bioremediation practices.

7. Conclusion and future perspectives

In textile, paper-pulp, and dyeing industries, many recalcitrant and synthetic dyes and organic materials are present in the effluent water that their disposal in the environment cause serious problems, especially in water reservoirs. Hence, these kinds of wastewater should be subjected to the effective treatment strategies to abate its environmental impacts. The biological approaches are more environmentally friendly and affordable compared with current established physical and chemical methods; though, none of these strategies would eliminate all pollutants in the industrial effluents due to the diverse nature of pollutants composition. Therefore, a combination of appropriate approaches is suggested based on the pollutant type, concentration, and recalcitrance to remove all existing harmful materials. It has been proven that filamentous fungal cells and their enzymes are able to efficiently remove organic materials from industrial effluents or transform them into less harmful compounds. Different genera and species of filamentous fungi or their consortia with other effective microorganisms can be precisely selected for use in treating various pollutants present in industrial wastewater along with other methods. Furthermore, filamentous fungal enzymes have a promising future in the industrial wastewater treatment technology as the constructed and tailored systems would be cell-free and more specific for the elimination of pollutants. Although filamentous fungi have been studied for their potential to treat wastewater, their role in this approach is not yet fully inferred. Preceding research on filamentous fungi in wastewater treatment has primarily been conducted in laboratory settings, and further work is required to determine the suitability of these methods for industrial applications. Therefore, additional laboratory experiments and pilot scale studies are necessary to establish the feasibility of using filamentous fungi for large-scale wastewater treatment processes. Accordingly, mycoremediation would ultimately help decrease the levels of pollutants in industrial wastewater, thereby safeguarding the environment and the well-being of many living organisms on our planet.

CRediT authorship contribution statement

Taner Sar: Writing – original draft, Visualization, Conceptualization. **Ariel Marchlewicz:** Writing – original draft. **Sharareh Harirchi:** Writing – review & editing, Writing – original draft. **Fani Th Mantzouridou:** Writing – original draft. **Muge Isleten Hosoglu:** Writing – original draft. **Meltem Yesilcimen Akbas:** Writing – original draft. **Coralie Hellwig:** Writing – original draft. **Mohammad J. Taherzadeh:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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References

Abd El-Zaher, E.H., 2010. Biodegradation of reactive dyes using soil fungal isolates and *Ganoderma resinaceum*. Ann. Microbiol. 60, 269–278.
Abdel-Raheam, H.E.F., Alrumman, S.A., Gadow, S.I., El-Sayed, M.H., Hikal, D.M., Hesham, A.E.-L., Ali, M.M.A., 2022. Optimization of *Monascus purpureus* for natural food pigments production on potato wastes and their application in ice lolly. Front. Microbiol. 13.
Abdul Karim, M.I., Ahmad Kamil, A.Q., 1989. Biological treatment of palm oil mill effluent using *Trichoderma viride*. Biol. Wastes 27 (2), 143–152.
Abrunhosa, L., Oliveira, F., Dantas, D., Gonçalves, C., Belo, I., 2013. Lipase production by *Aspergillus ibericus* using olive mill wastewater. Bioprocess Biosyst. Eng. 36 (3), 285–291.
Afonso-Olivares, C., Sosa-Ferrera, Z., Santana-Rodríguez, J.J., 2017. Occurrence and environmental impact of pharmaceutical residues from conventional and natural

wastewater treatment plants in Gran Canaria (Spain). Sci. Total Environ. 599-600, 934–943.
Aisien, E.T., Igbinosa, I.H., 2019. Production, purification, and characterization of α-amylase from *Aspergillus niger*, *Aspergillus flavus* and *Penicillium expansum* using cassava peels as substrate. Niger. J. Biotechnol. 36 (2), 114–126.
Ajibo, A.E., Said, R.O., 2023. Production of gluconic acid from sweet potato peels using naturally occurring fungi by submerged fermentation. Bio-Research 21 (1), 1827–1837.
Al-Maadheed, S., Goktepe, I., Latiff, A.B.A., Shomar, B., 2019. Antibiotics in hospital effluent and domestic wastewater treatment plants in Doha, Qatar. J. Water Process. Eng. 28, 60–68.
Alaguprathana, M., Poonkothai, M., Ameen, F., Bhat, S.A., Mythili, R., Sudhakar, C., 2022. Sodium hydroxide pre-treated *Aspergillus flavus* biomass for the removal of reactive black 5 and its toxicity evaluation. Environ. Res. 214, 113859.
Ali, M., Sreekrishnan, T.R., 2001. Aquatic toxicity from pulp and paper mill effluents: a review. Adv. Environ. Res. 5 (2), 175–196.
Almuhayawi, M.S., Hassan, E.A., Alkuwaity, K.K., Abujamel, T.S., Mokhtar, J.A., Niyazi, H.A., Almasaudi, S.B., Alamri, T.A., Najjar, A.A., Zabermawi, N.M., Azhar, E. I., Makki, R.M., Niyazi, H.A., Harakeh, S.M., 2023. Enzymatic-based hydrolysis of digested potato peel wastes by amylase producing fungi to improve biogas generation. In: Catalysts, Vol. 13.
Aloui, F., Khoufi, S., Loukil, S., Sayadi, S., 2009. Performances of an activated sludge process for the treatment of fish processing saline wastewater. Desalination 246 (1), 389–396.
Ameen, F., Dawoud, T.M., Alshehrei, F., Alsamhary, K., Almansob, A., 2021. Decolorization of acid blue 29, disperse red 1 and Congo red by different indigenous fungal strains. Chemosphere 271, 129532.
Amin, M.M., Bina, B., Ebrahimi, A., Yavari, Z., Mohammadi, F., Rahimi, S., 2018. The occurrence, fate, and distribution of natural and synthetic hormones in different types of wastewater treatment plants in Iran. Chin. J. Chem. Eng. 26 (5), 1132–1139.
Arikan, E.B., Isik, Z., Bouras, H.D., Dizge, N., 2019. Investigation of immobilized filamentous fungi for treatment of real textile industry wastewater using up flow packed bed bioreactor. Bioresour. Technol. Rep. 7, 100197.
Asadollahzadeh, M., Ghasemian, A., Saraeian, A., Resalati, H., Lennartsson, P.R., Taherzadeh, M.J., 2017a. Using spent sulfite liquor for valuable fungal biomass production by *Aspergillus oryzae*. Nord. Pulp Pap. Res. J. 32 (4), 630–638.
Asadollahzadeh, M., Ghasemian, A., Saraeian, A., Resalati, H., Taherzadeh, M.J., 2018. Production of fungal biomass protein by filamentous fungi cultivation on liquid waste streams from pulping process. BioResources 13 (3), 5013–5031.
Asadollahzadeh, M.T., Ghasemian, A., Saraeian, A.R., Resalati, H., Lennartsson, P.R., Taherzadeh, M.J., 2017b. Ethanol and biomass production from spent sulfite liquor by filamentous fungi. Int. J. Biotechnol. Bioeng. 11 (10), 718–724.
Asgher, M., Azim, N., Bhatti, H.N., 2009. Decolorization of practical textile industry effluents by white rot fungus *Coriolus versicolor* IBL-04. Biochem. Eng. J. 47 (1), 61–65.
Ashraf, M., Ali, S., Attia Iram, R.A., Abbas, G., Sajjad-ur-Rahman, K., 2017. Isolation and screening of biodegrading fungi from kitchen waste and optimization of physico-chemical conditions for enhanced biodegradation. J. Agric. Basic Sci. 2 (1).
Ashrafi, O., Yerushalmi, L., Haghighat, F., 2015. Wastewater treatment in the pulp-and-paper industry: a review of treatment processes and the associated greenhouse gas emission. J. Environ. Manag. 158, 146–157.
Assress, H.A., Selvarajan, R., Nyoni, H., Ntushelo, K., Mamba, B.B., Msagati, T.A.M., 2019. Diversity, co-occurrence and implications of fungal communities in wastewater treatment plants. Sci. Rep. 9 (1), 14056.
Avci, H., Özcan, T., 2020. The characterisation of dairy industry waste buttermilk from different butter processing procedures. Fresenius Environ. Bull. 29 (7).
Avşar, E., Demirer, G.N., 2008. Cleaner production opportunity assessment study in SEKA Balikesir pulp and paper mill. J. Clean. Prod. 16 (4), 422–431.
Awasthi, M.K., Paul, A., Kumar, V., Sar, T., Kumar, D., Sarsaiya, S., Liu, H., Zhang, Z., Binod, P., Sindhu, R., 2022. Recent trends and developments on integrated biochemical conversion process for valorization of dairy waste to value added bioproducts: a review. Bioresour. Technol. 344, 126193.
Awasthi, M.K., Kumar, V., Hellwig, C., Wikandari, R., Harirchi, S., Sar, T., Wainaina, S., Sindhu, R., Binod, P., Zhang, Z., Taherzadeh, M.J., 2023. Filamentous fungi for sustainable vegan food production systems within a circular economy: present status and future prospects. Food Res. Int. 164, 112318.
Azhar, B., Saadun, N., Prideaux, M., Lindenmayer, D.B., 2017. The global palm oil sector must change to save biodiversity and improve food security in the tropics. J. Environ. Manag. 203, 457–466.
Badia-Fabregat, M., Lucas, D., Tuomivirta, T., Fritze, H., Pennanen, T., Rodríguez-Mozaz, S., Barceló, D., Caminal, G., Vicent, T., 2017. Study of the effect of the bacterial and fungal communities present in real wastewater effluents on the performance of fungal treatments. Sci. Total Environ. 579, 366–377.
Barker, T.W., Worgan, J.T., 1981. The utilisation of palm oil processing effluents as substrates for microbial protein production by the fungus *Aspergillus oryzae*. Eur. J. Appl. Microbiol. Biotechnol. 11 (4), 234–240.
Beltrán-Flores, E., Pla-Ferriol, M., Martínez-Alonso, M., Gaju, N., Blánquez, P., Sarrà, M., 2022. Fungal bioremediation of agricultural wastewater in a long-term treatment: biomass stabilization by immobilization strategy. J. Hazard. Mater. 439, 129614.
Bernal, S.P.F., Gritti, M.A., dos Santos, V.P., Ottoni, J.R., de Oliveira, V.M., Peichoto, M. E., Passarini, M.R.Z., 2021. Pharmaceutical biotechnological potential of filamentous fungi isolated from textile industry. Arch. Microbiol. 203 (7), 3933–3944.
Betancur, M., Bonelli, P.R., Velásquez, J.A., Cukierman, A.L., 2009. Potentiality of lignin from the Kraft pulping process for removal of trace nickel from wastewater: effect of demineralisation. Bioresour. Technol. 100 (3), 1130–1137.
Boonyarit, J., Polburee, P., Khaenda, B., Zhao, Z.K., Limtong, S., 2020. Lipid production from sugarcane top hydrolysate and crude glycerol with *Rhodosporidiobolus fluvialis* using a two-stage batch-cultivation strategy with separate optimization of each stage. In: Microorganisms, Vol. 8.
Braho, V., Sar, T., Taherzadeh, M.J., 2023. Cultivation of edible filamentous fungi on pomegranate by-products as feedstocks to produce mycoprotein. In: Systems Microbiology and Biomanufacturing, pp. 1–12.
Brancoli, P., Gmoser, R., Taherzadeh, M.J., Bolton, K., 2021. The use of life cycle assessment in the support of the development of fungal food products from surplus bread. Fermentation 7 (3), 173.
Brar, A., Kumar, M., Vivekanand, V., Pareek, N., 2019. Phycoremediation of textile effluent-contaminated water bodies employing microalgae: nutrient sequestration and biomass production studies. Int. J. Environ. Sci. Technol. 16 (12), 7757–7768.
Britz, T.J., Van Schalkwyk, C., Hung, Y.-T., 2006. Treatment of dairy processing wastewaters. Waste Treat. Food Process. Ind. 1.
Campos-Mañas, M.C., Plaza-Bolaños, P., Sánchez-Pérez, J.A., Malato, S., Agüera, A., 2017. Fast determination of pesticides and other contaminants of emerging concern in treated wastewater using direct injection coupled to highly sensitive ultra-high performance liquid chromatography-tandem mass spectrometry. J. Chromatogr. A 1507, 84–94.
Carvalho, F., Prazeres, A.R., Rivas, J., 2013. Cheese whey wastewater: characterization and treatment. Sci. Total Environ. 445–446, 385–396.
Chadni, Z., Rahaman, M.H., Jerin, I., Hoque, K.M.F., Reza, M.A., 2017. Extraction and optimisation of red pigment production as secondary metabolites from *Talaromyces verruculosus* and its potential use in textile industries. Mycology 8 (1), 48–57.
Chandra, R., Raj, A., Yadav, S., Patel, D.K., 2009. Reduction of pollutants in pulp paper mill effluent treated by PCP-degrading bacterial strains. Environ. Monit. Assess. 155 (1), 1–11.
Chandra, R., Castillo-Zacarias, C., Delgado, P., Parra-Saldívar, R., 2018. A biorefinery approach for dairy wastewater treatment and product recovery towards establishing a biorefinery complexity index. J. Clean. Prod. 183, 1184–1196.
Chatterjee, S., Venkata Mohan, S., 2022. Fungal biorefinery for sustainable resource recovery from waste. Bioresour. Technol. 345, 126443.
Chen, H., Zhang, H., Tian, J., Shi, J., Linhardt, R.J., Ye, T.D.X., Chen, S., 2019. Recovery of high value-added nutrients from fruit and vegetable industrial wastewater. Compr. Rev. Food Sci. Food Saf. 18 (5), 1388–1402.
Chipeta, Z.A., du Preez, J.C., Szakacs, G., Christopher, L., 2005. Xylanase production by fungal strains on spent sulphite liquor. Appl. Microbiol. Biotechnol. 69 (1), 71–78.
Chowdhury, P., Viraraghavan, T., Srinivasan, A., 2010. Biological treatment processes for fish processing wastewater — a review. Bioresour. Technol. 101 (2), 439–449.
Chuppa-Tostain, G., Tan, M., Adelard, L., Shum-Cheong-Sing, A., François, J.-M., Caro, Y., Petit, T., 2020. Evaluation of filamentous fungi and yeasts for the biodegradation of sugarcane distillery wastewater. Microorganisms Vol. 8.
Citkowska, A., Szekalska, M., Winnicka, K., 2019. Possibilities of fucoidan utilization in the development of pharmaceutical dosage forms. Mar. Drugs 17.
Corso, C.R., Maganha de Almeida, A.C., 2009. Bioremediation of dyes in textile effluents by *Aspergillus oryzae*. Microb. Ecol. 57 (2), 384–390.
Cristóvão, R.O., Botelho, C.M., Martins, R.J.E., Loureiro, J.M., Boaventura, R.A.R., 2014. Primary treatment optimization of a fish canning wastewater from a Portuguese plant. Water Resour. Ind. 6, 51–63.
D'Alessio, M., Onanong, S., Snow, D.D., Ray, C., 2018. Occurrence and removal of pharmaceutical compounds and steroids at four wastewater treatment plants in Hawai'i and their environmental fate. Sci. Total Environ. 631-632, 1360–1370.
De Leonardis, A., Macciola, V., Iftikhar, A., 2023. Present and future perspectives on the use of olive-oil mill wastewater in food applications. In: Souabi, S., Anouzla, A. (Eds.), Wastewater from Olive Oil Production: Environmental Impacts, Treatment and Valorisation. Springer International Publishing, Cham, pp. 85–105.
DellaGreca, M., Brigante, M., Isidori, M., Nardelli, A., Previtera, L., Rubino, M., Temussi, F., 2003. Phototransformation and ecotoxicity of the drug Naproxen-Na. Environ. Chem. Lett. 1 (4), 237–241.
Dermeche, S., Nadour, M., Larroche, C., Moulti-Mati, F., Michaud, P., 2013. Olive mill wastes: biochemical characterizations and valorization strategies. Process Biochem. 48 (10), 1532–1552.
Dey, P., Rangarajan, V., Singh, J., Nayak, J., Dilip, K.J., 2022. Current perspective on improved fermentative production and purification of fungal cellulases for successful biorefinery applications: a brief review. Biomass Convers. Biorefinery 12 (3), 967–995.
Dhanavade, M.J., Patil, P.J., 2023. 12 — Yeast and fungal mediated degradation of synthetic dyes. In: Govindwar, S.P., Kurade, M.B., Jeon, B.-H., Pandey, A. (Eds.), Current Developments in Bioengineering and Biotechnology. Elsevier, pp. 371–409.
Dhillon, S.S., Gill, R.K., Gill, S.S., Singh, M., 2004. Studies on the utilization of citrus peel for pectinase production using fungus *Aspergillus niger*. Int. J. Environ. Stud. 61 (2), 199–210.
Díaz-Cruz, M.S., Barceló, D., 2006. Determination of antimicrobial residues and metabolites in the aquatic environment by liquid chromatography tandem mass spectrometry. Anal. Bioanal. Chem. 386 (4), 973–985.
Dominic, D., Baidurah, S., 2022. Recent developments in biological processing technology for palm oil mill effluent treatment—a review. Biology 11.
Dong, W., Yin, X., Qi, C., Wei, T., Wei, L., Yang, J., Mu, J., Teraoka, H., Dong, W., 2023. Reduced pigmentation and thyroid hormone disruption in zebrafish embryos caused by industrial sludge near Bohai Bay, China. In: Water Biology and Security, p. 100190.
Dzurendova, S., Losada, C.B., Dupuy-Galet, B.X., Fjær, K., Shapaval, V., 2022. Mucoromycota fungi as powerful cell factories for modern biorefinery. Appl. Microbiol. Biotechnol. 106 (1), 101–115.

Ekstrand, E.-M., Larsson, M., Truong, X.-B., Cardell, L., Borgström, Y., Björn, A., Ejlertsson, J., Svensson, B.H., Nilsson, F., Karlsson, A., 2013. Methane potentials of the Swedish pulp and paper industry — a screening of wastewater effluents. Appl. Energy 112, 507–517.

El Mekawy, A., Diels, L., Bertin, L., De Wever, H., Pant, D., 2014. Potential biovalorization techniques for olive mill biorefinery wastewater. Biofuels Bioprod. Biorefin. 8 (2), 283–293.

Escalante, M.R.T., Acanto, R.B., Conlu, M.T.N., Langcoy, M.G.F., Lirazan, S.V., Mario, J. A.B., 2022. Growth of *Trichoderma harzianum* using starch-based household kitchen wastes. Growth 2 (4).

Espinosa-Ortiz, E.J., Rene, E.R., Pakshirajan, K., van Hullebusch, E.D., Lens, P.N.L., 2016. Fungal pelleted reactors in wastewater treatment: applications and perspectives. Chem. Eng. J. 283, 553–571.

Esterhuizen, M., Behnam Sani, S., Wang, L., Kim, Y.J., Pflugmacher, S., 2021. Mycoremediation of acetaminophen: culture parameter optimization to improve efficacy. Chemosphere 263, 128117.

Esterhuizen-Londt, M., Schwartz, K., Pflugmacher, S., 2016. Using aquatic fungi for pharmaceutical bioremediation: uptake of acetaminophen by *Mucor hiemalis* does not result in an enzymatic oxidative stress response. Fungal Biol. 120 (10), 1249–1257.

Ezeonu, C.S., Otiwa, S.O., 2020. Quality Assessment of Fungal Synthesized Bio-surfactants From Agro-wastes (Cassava, Yam and Sweet Potato Peels).

Ferreira, J.A., Varjani, S., Taherzadeh, M.J., 2020. A critical review on the ubiquitous role of filamentous fungi in pollution mitigation. Curr. Pollut. Rep. 6 (4), 295–309.

Fu, Y.-Q., Li, S., Zhu, H.-Y., Jiang, R., Yin, L.-F., 2012. Biosorption of copper (II) from aqueous solution by mycelial pellets of *Rhizopus oryzae*. Afr. J. Biotechnol. 11 (6), 1403–1411.

Gao, F., Peng, Y.-Y., Li, C., Yang, G.-J., Deng, Y.-B., Xue, B., Guo, Y.-M., 2018. Simultaneous nutrient removal and biomass/lipid production by *Chlorella* sp. in seafood processing wastewater. Sci. Total Environ. 640–641, 943–953.

Gao, Q., Cui, Z., Zhang, J., Bao, J., 2014. Lipid fermentation of corncob residues hydrolysate by oleaginous yeast *Trichosporon cutaneum*. Bioresour. Technol. 152, 552–556.

Gassara, F., Brar, S.K., Tyagi, R.D., Verma, M., Surampalli, R.Y., 2010. Screening of agro-industrial wastes to produce ligninolytic enzymes by *Phanerochaete chrysosporium*. Biochem. Eng. J. 49 (3), 388–394.

Geethakarthi, A., 2021. Application of Sustainable and Low-Cost Sludge-Based Adsorbents for Textile Dye Degradation. In: Muthu, S.S. (Ed.), Advances in Textile Waste Water Treatments. Springer, Singapore. Singapore, pp. 25–88.

Ghaly, A.E., Ananthashankar, R., Alhattab, M., Ramakrishnan, V.V., 2014. Production, characterization and treatment of textile effluents: a critical review. J. Chem. Eng. Process. Technol. 5 (1), 1–19.

Ghazal, F.M., Mahdy, E.S.M., El-Fattah, M.S.A., El-Sadany, A., Elg, Y., Doha, N.M.E., 2018. The use of microalgae in bioremediation of the textile wastewater effluent. Nat. Sci. 16, 98–104.

Ghosh, S., Rusyn, I., Dmytruk, O.V., Dmytruk, K.V., Onyeaka, H., Gryzenhout, M., Gafforov, Y., 2023. Filamentous fungi for sustainable remediation of pharmaceutical compounds, heavy metal and oil hydrocarbons. Front. Bioeng. Biotechnol. 11, 1106973.

Golovko, O., Kumar, V., Fedorova, G., Randak, T., Grabic, R., 2014. Seasonal changes in antibiotics, antidepressants/psychiatric drugs, antihistamines and lipid regulators in a wastewater treatment plant. Chemosphere 111, 418–426.

Gonzalez-Diaz, A., Pataquiva-Mateus, A., García-Núñez, J.A., 2021. Recovery of palm phytonutrients as a potential market for the by-products generated by palm oil mills and refineries—a review. Food Biosci. 41, 100916.

Goodwin, L., Carra, I., Campo, P., Soares, A., 2017. Treatment options for reclaiming wastewater produced by the pesticide industry. Int. J. Water Wastewater Treat. 4 (1).

Gopal, P.M., Sivaram, N.M., Barik, D., 2019. Chapter 7 — Paper industry wastes and energy generation from wastes. In: Barik, D. (Ed.), Energy from Toxic Organic Waste for Heat and Power Generation. Woodhead Publishing, pp. 83–97.

Górny, D., Guzik, U., Hupert-Kocurek, K., Wojcieszyńska, D., 2019. A new pathway for naproxen utilisation by *Bacillus thuringiensis* B1(2015b) and its decomposition in the presence of organic and inorganic contaminants. J. Environ. Manag. 239, 1–7.

Guedez, A.A., Püttmann, W., 2014. Printing ink and paper recycling sources of TMDD in wastewater and rivers. Sci. Total Environ. 468–469, 671–676.

Gupta, G.K., Dixit, M., Kapoor, R.K., Shukla, P., 2022. Xylanolytic enzymes in pulp and paper industry: new technologies and perspectives. Mol. Biotechnol. 64 (2), 130–143.

Gupta, V.K., Suhas., 2009. Application of low-cost adsorbents for dye removal — a review. J. Environ. Manag. 90 (8), 2313–2342.

Gurke, R., Rößler, M., Marx, C., Diamond, S., Schubert, S., Oertel, R., Fauler, J., 2015. Occurrence and removal of frequently prescribed pharmaceuticals and corresponding metabolites in wastewater of a sewage treatment plant. Sci. Total Environ. 532, 762–770.

Haddaoui, I., Mahjoub, O., Mahjoub, B., Boujelben, A., Di Bella, G., 2016. Occurrence and distribution of PAHs, PCBs, and chlorinated pesticides in Tunisian soil irrigated with treated wastewater. Chemosphere 146, 195–205.

Hamdi, S., Allala, F., Mechri, S., Bouacem, K., Rekik, H., Hacene, H., Jaouadi, B., Le Roes-Hill, M., Jaouadi, N.Z., 2022. Biochemical and molecular characterization of a new heme peroxidase from *Aspergillus niger* CTM10002, and its application in textile reactive dye decolorization. Process Biochem. 121, 619–634.

Hamimed, S., Landoulsi, A., Chatti, A., 2021. The bright side of olive mill wastewater: valuables bioproducts after bioremediation. Int. J. Environ. Sci. Technol. 18 (12), 4053–4074.

Hashemi, S.S., Karimi, K., Taherzadeh, M.J., 2021. Integrated process for protein, pigments, and biogas production from baker's yeast wastewater using filamentous fungi. Bioresour. Technol. 337, 125356.

Hassan, S.R., Zwain, H.M., Zaman, N.Q., Dahlan, I., 2014. Recycled paper mill effluent treatment in a modified anaerobic baffled reactor: start-up and steady-state performance. Environ. Technol. 35 (3), 294–299.

Hellwig, C., 2023. Engagement with fungi-based food: recovery and valorization of resources for food. In: Faculty of Textiles, Engineering and Business. University of Borås, Borås, p. 139. Vol. Doctor of Philosophy.

Hellwig, C., Gmoser, R., Lundin, M., Taherzadeh, M.J., Rousta, K., 2020. Fungi burger from stale bread? A case study on perceptions of a novel protein-rich food product made from an edible fungus. Foods 9 (8), 1112.

Hellwig, C., Rousta, N., Wikandari, R., Taherzadeh, M.J., Häggblom-Kronlöf, G., Bolton, K., Rousta, K., 2022. Household fermentation of leftover bread to nutritious food. Waste Manag. 150, 39–47.

Hellwig, C., Bolton, K., Häggblom-Kronlöf, G., Rousta, K., 2023. Aspects affecting food choice in daily life as well as drivers and barriers to engagement with fungi-based food—a qualitative perspective. Sustainability 15 (1), 317.

Huang, Y., Xiao, L., Li, F., Xiao, M., Lin, D., Long, X., Wu, Z., 2018. Microbial degradation of pesticide residues and an emphasis on the degradation of cypermethrin and 3-phenoxy benzoic acid: a review. Molecules 23.

Hubbard, L.E., Kolpin, D.W., Givens, C.E., Blackwell, B.R., Bradley, P.M., Gray, J.L., Lane, R.F., Masoner, J.R., McCleskey, R.B., Romanok, K.M., Sandstrom, M.W., Smalling, K.L., Villeneuve, D.L., 2022. Food, beverage, and feedstock processing facility wastewater: a unique and underappreciated source of contaminants to U.S. streams. Environ. Sci. Technol. 56 (2), 1028–1040.

Hussein, F.H., 2013. Chemical properties of treated textile dyeing wastewater. Asian J. Chem. 25 (16).

Hüttner, S., Johansson, A., Gonçalves Teixeira, P., Achterberg, P., Nair, R.B., 2020. Recent advances in the intellectual property landscape of filamentous fungi. Fungal Biol. Biotechnol. 7 (1), 16.

Huuha, T.S., Kurniawan, T.A., Sillanpää, M.E.T., 2010. Removal of silicon from pulping whitewater using integrated treatment of chemical precipitation and evaporation. Chem. Eng. J. 158 (3), 584–592.

IEA, 2023. International Energy Agency, Vol. 2023.

International Olive Council. Vol. 2023.

Iyanagi, T., 2007. Molecular mechanism of phase I and phase II drug-metabolizing enzymes: implications for detoxification. In: International Review of Cytology, Vol. 260. Academic Press, pp. 35–112.

Jarosz-Wilkołazka, A., Kochmańska-Rdest, J., Malarczyk, E., Wardas, W., Leonowicz, A., 2002. Fungi and their ability to decolourize azo and anthraquinonic dyes. Enzym. Microb. Technol. 30 (4), 566–572.

Jenkins, N.E., Grzywacz, D., 2000. Quality control of fungal and viral biocontrol agents-assurance of product performance. Biocontrol Sci. Tech. 10 (6), 753–777.

Jiang, Y., Marang, L., Tamis, J., van Loosdrecht, M.C.M., Dijkman, H., Kleerebezem, R., 2012. Waste to resource: converting paper mill wastewater to bioplastic. Water Res. 46 (17), 5517–5530.

Joshi, V.J., Santani, D.D., 2012. Physicochemical characterization and heavy metal concentration in effluent of textile industry. Univ. J. Environ. Res. Technol. 2 (2).

Juárez-Hernández, J., Castillo-Hernández, D., Pérez-Parada, C., Nava-Galicia, S., Cuervo-Parra, J.A., Surian-Cruz, E., Díaz-Godínez, G., Sánchez, C., Bibbins-Martínez, M., 2021. Isolation of fungi from a textile industry effluent and the screening of their potential to degrade industrial dyes. J. Fungi 7.

Kamali, M., Gameiro, T., Costa, M.E.V., Capela, I., 2016. Anaerobic digestion of pulp and paper mill wastes — an overview of the developments and improvement opportunities. Chem. Eng. J. 298, 162–182.

Kansal, S.K., Singh, M., Sud, D., 2008. Effluent quality at kraft/soda agro-based paper mills and its treatment using a heterogeneous photocatalytic system. Desalination 228 (1), 183–190.

Karatay, S.E., Aksu, Z., Özeren, İ., Dönmez, G., 2023. Potentiality of newly isolated *Aspergillus tubingensis* in biosorption of textile dyes: equilibrium and kinetic modeling. Biomass Convers. Biorefinery 13 (6), 4777–4784.

Karimi, S., Mahboobi Soofiani, N., Lundh, T., Mahboubi, A., Kiessling, A., Taherzadeh, M.J., 2019. Evaluation of filamentous fungal biomass cultivated on vinasse as an alternative nutrient source of fish feed: protein, lipid, and mineral composition. In: Fermentation, Vol. 5.

Karrasch, B., Parra, O., Cid, H., Mehrens, M., Pacheco, P., Urrutia, R., Valdovinos, C., Zaror, C., 2006. Effects of pulp and paper mill effluents on the microplankton and microbial self-purification capabilities of the Biobío River, Chile. Sci. Total Environ. 359 (1), 194–208.

Kaushik, P., Malik, A., 2010. Alkali, thermo and halo tolerant fungal isolate for the removal of textile dyes. Colloids Surf. B: Biointerfaces 81 (1), 321–328.

Kc, S., Upadhyaya, J., Joshi, D.R., Lekhak, B., Kumar Chaudhary, D., Raj Pant, B., Raj Bajgai, T., Dhital, R., Khanal, S., Koirala, N., Raghavan, V., 2020. Production, characterization, and industrial application of pectinase enzyme isolated from fungal strains. Fermentation Vol. 6.

Kehinde, F., Aziz, H.A., 2014. Textile waste water and the advanced oxidative treatment process, an overview. Int. J. Innov. Res. Sci. Eng. Technol. 3 (8), 15310–15317.

Khan, K., Kumar, P.V.V., Ahmad, A., Riaz, T., Anwer, W., Suleman, M., Ajmal, O., Ali, T., Chaitanya, A.V.K., 2011. Requirement development life cycle: the industry practices. In: 2011 Ninth International Conference on Software Engineering Research, Management and Applications. IEEE, pp. 12–16.

Khan, N.A., Ahmed, S., Farooqi, I.H., Ali, I., Vambol, V., Changani, F., Yousefi, M., Vambol, S., Khan, S.U., Khan, A.H., 2020. Occurrence, sources and conventional treatment techniques for various antibiotics present in hospital wastewaters: a critical review. TrAC Trends Anal. Chem. 129, 115921.

Kharel, S., Stapf, M., Miehe, U., Ekblad, M., Cimbritz, M., Falås, P., Nilsson, J., Sehlén, R., Bregendahl, J., Bester, K., 2021. Removal of pharmaceutical metabolites in wastewater ozonation including their fate in different post-treatments. Sci. Total Environ. 759, 143989.

Khasawneh, O.F.S., Palaniandy, P., 2021. Occurrence and removal of pharmaceuticals in wastewater treatment plants. Process. Saf. Environ. Prot. 150, 532–556.

Khdair, A., Abu-Rumman, G., 2020. Sustainable environmental management and valorization options for olive mill byproducts in the Middle East and North Africa (MENA) region. In: Processes, Vol. 8.

Köck-Schulmeyer, M., Villagrasa, M., López de Alda, M., Céspedes-Sánchez, R., Ventura, F., Barceló, D., 2013. Occurrence and behavior of pesticides in wastewater treatment plants and their environmental impact. Sci. Total Environ. 458–460, 466–476.

Koistinen, J., Paasivirta, J., Nevalainen, T., Lahtiperä, M., 1994. Chlorinated fluorenes and alkylfluorenes in bleached kraft pulp and pulp mill discharges. Chemosphere 28 (12), 2139–2150.

Kolev Slavov, A., 2017. General characteristics and treatment possibilities of dairy wastewater—a review. Food Technol. Biotechnol. 55 (1), 14–28.

K'Oreje, K.O., Kandie, F.J., Vergeynst, L., Abira, M.A., Van Langenhove, H., Okoth, M., Demeestere, K., 2018. Occurrence, fate and removal of pharmaceuticals, personal care products and pesticides in wastewater stabilization ponds and receiving rivers in the Nzoia Basin, Kenya. Sci. Total Environ. 637-638, 336–348.

Kot-Wasik, A., Jakimska, A., Śliwka-Kaszyńska, M., 2016. Occurrence and seasonal variations of 25 pharmaceutical residues in wastewater and drinking water treatment plants. Environ. Monit. Assess. 188 (12), 661.

Kumar, A., Yadav, A.N., Mondal, R., Kour, D., Subrahmanyam, G., Shabnam, A.A., Khan, S.A., Yadav, K.K., Sharma, G.K., Cabral-Pinto, M., Fagodiya, R.K., Gupta, D.K., Hota, S., Malyan, S.K., 2021. Myco-remediation: a mechanistic understanding of contaminants alleviation from natural environment and future prospect. Chemosphere 284, 131325.

Kunjadia, P.D., Sanghvi, G.V., Kunjadia, A.P., Mukhopadhyay, P.N., Dave, G.S., 2016. Role of ligninolytic enzymes of white rot fungi (*Pleurotus* spp.) grown with azo dyes. SpringerPlus 5, 1–9.

Kurade, M.B., Waghmode, T.R., Jadhav, M.U., Jeon, B.-H., Govindwar, S.P., 2015. Bacterial–yeast consortium as an effective biocatalyst for biodegradation of sulphonated azo dye Reactive Red 198. RSC Adv. 5 (29), 23046–23056.

Kurade, M.B., Waghmode, T.R., Chakankar, M., Awasthi, M.K., Dawkar, V., Jeon, B.-H., 2023. Microbial consortium as an effective biocatalyst for the decolorization of textile dyes wastewater. In: Current Developments in Bioengineering and Biotechnology. Elsevier, pp. 473–511.

Kwak, K., Ji, K., Kho, Y., Kim, P., Lee, J., Ryu, J., Choi, K., 2018. Chronic toxicity and endocrine disruption of naproxen in freshwater waterfleas and fish, and steroidogenic alteration using H295R cell assay. Chemosphere 204, 156–162.

Lanfranconi, I., Ceretta, M.B., Bertola, N., Wolski, E.A., Durruty, I., 2022. Textile dyeing wastewater treatment by *Penicillium chrysogenum*: design of a sustainable process. Water Sci. Technol. 86 (2), 292–301.

Lawson, H.D., Walton, S.P., Chan, C., 2021. Metal–organic frameworks for drug delivery: a design perspective. ACS Appl. Mater. Interfaces 13 (6), 7004–7020.

Legorreta-Castañeda, A.J., Lucho-Constantino, C.A., Beltrán-Hernández, R.I., Coronel-Olivares, C., Vázquez-Rodríguez, G.A., 2020. Biosorption of water pollutants by fungal pellets. Water 12 (4), 1155.

Leitão, A.L., 2009. Potential of *Penicillium* species in the bioremediation field. Int. J. Environ. Res. Public Health 6, 1393–1417.

Li, L., Liang, T., Liu, W., Liu, Y., Ma, F., 2020. A comprehensive review of the mycelial pellet: research status, applications, and future prospects. Ind. Eng. Chem. Res. 59 (39), 16911–16922.

Liew, W.L., Kassim, M.A., Muda, K., Loh, S.K., 2006. Feasibility Study on Palm Oil Processing Wastes towards Achieving Zero Discharge.

Liew, W.L., Kassim, M.A., Muda, K., Loh, S.K., Affam, A.C., 2015. Conventional methods and emerging wastewater polishing technologies for palm oil mill effluent treatment: a review. J. Environ. Manag. 149, 222–235.

Lim, S.-L., Chu, W.-L., Phang, S.-M., 2010. Use of *Chlorella vulgaris* for bioremediation of textile wastewater. Bioresour. Technol. 101 (19), 7314–7322.

Liu, F., Nielsen, A.H., Vollertsen, J., 2019. Sorption and degradation potential of pharmaceuticals in sediments from a stormwater retention pond. Water 11.

Liu, W., Chao, Y., Yang, X., Bao, H., Qian, S., 2004. Biodecolorization of azo, anthraquinonic and triphenylmethane dyes by white-rot fungi and a laccase-secreting engineered strain. J. Ind. Microbiol. Biotechnol. 31 (3), 127–132.

Logroño, W., Pérez, M., Urquizo, G., Kadier, A., Echeverría, M., Recalde, C., Rákhely, G., 2017. Single chamber microbial fuel cell (SCMFC) with a cathodic microalgal biofilm: a preliminary assessment of the generation of bioelectricity and biodegradation of real dye textile wastewater. Chemosphere 176, 378–388.

Madadi, R., Bester, K., 2021. Fungi and biochar applications in bioremediation of organic micropollutants from aquatic media. Mar. Pollut. Bull. 166, 112247.

Majumder, A., Gupta, B., Gupta, A.K., 2019. Pharmaceutically active compounds in aqueous environment: a status, toxicity and insights of remediation. Environ. Res. 176, 108542.

Manai, I., Miladi, B., El Mselmi, A., Smaali, I., Ben Hassen, A., Hamdi, M., Bouallagui, H., 2016. Industrial textile effluent decolourization in stirred and static batch cultures of a new fungal strain *Chaetomium globosum* IMA1 KJ472923. J. Environ. Manag. 170, 8–14.

Manekar, P., Patkar, G., Aswale, P., Mahure, M., Nandy, T., 2014. Detoxifying of high strength textile effluent through chemical and bio-oxidation processes. Bioresour. Technol. 157, 44–51.

Mani, S., Chowdhary, P., Bharagava, R.N., 2019. Textile wastewater dyes: toxicity profile and treatment approaches. In: Bharagava, R.N., Chowdhary, P. (Eds.), Emerging and Eco-friendly Approaches for Waste Management. Springer Singapore, Singapore, pp. 219–244.

Manoli, K., Morrison, L.M., Sumarah, M.W., Nakhla, G., Ray, A.K., Sharma, V.K., 2019. Pharmaceuticals and pesticides in secondary effluent wastewater: identification and enhanced removal by acid-activated ferrate(VI). Water Res. 148, 272–280.

Marchlewicz, A., Guzik, U., Smułek, W., Wojcieszyńska, D., 2017. Exploring the degradation of ibuprofen by *Bacillus thuringiensis* B1(2015b): the new pathway and factors affecting degradation. In: Molecules, Vol. 22.

Marchlewicz, A., Guzik, U., Hupert-Kocurek, K., Wojcieszyńska, D., 2023. Evaluation of the defined bacterial consortium efficacy in the biodegradation of NSAIDs. Molecules 28.

María Noel, C., 2017. Pulp mill wastewater: characteristics and treatment. In: Robina, F., Zaki, A. (Eds.), Biological Wastewater Treatment and Resource Recovery. IntechOpen, Rijeka. Ch. 7.

Mastralexi, A., Tsimidou, M.Z., 2021. The potential of virgin olive oil from cv. Chondrolia Chalkidikis and Chalkidiki (Greece) to bear health claims according to the European legislation. In: Molecules, Vol. 26.

Michalska, K., Goszkiewicz, A., Skalska, K., Kołodziejczyk, E., Markiewicz, J., Majzer, R., Siedlecki, M., 2021. Treatment of industrial wastewaters and liquid waste by fungi. In: Encyclopedia of Mycology, Volume 2.

Modenbach, A.A., Nokes, S.E., 2012. The use of high-solids loadings in biomass pretreatment—a review. Biotechnol. Bioeng. 109 (6), 1430–1442.

Mohammad, N., Alam, M.Z., Kabbashi, N.A., Ahsan, A., 2012. Effective composting of oil palm industrial waste by filamentous fungi: a review. Resour. Conserv. Recycl. 58, 69–78.

Mohammad, S., Baidurah, S., Kobayashi, T., Ismail, N., Leh, C.P., 2021. Palm oil mill effluent treatment processes—a review. In: Processes, Vol. 9.

Monetti, J., Nieradzik, L., Freguia, S., Choi, P.M., O'Brien, J.W., Thomas, K.V., Ledezma, P., 2022. Urea hydrolysis and long-term storage of source-separated urine for reuse as fertiliser is insufficient for the removal of anthropogenic micropollutants. Water Res. 222, 118891.

More, T., Yan, S., Tyagi, R., Surampalli, R., 2010. Potential use of filamentous fungi for wastewater sludge treatment. Bioresour. Technol. 101 (20), 7691–7700.

Morya, R., Kumar, M., Tyagi, I., Kumar Pandey, A., Park, J., Raj, T., Sirohi, R., Kumar, V., Kim, S.-H., 2022. Recent advances in black liquor valorization. Bioresour. Technol. 350, 126916.

Münze, R., Hannemann, C., Orlinskiy, P., Gunold, R., Paschke, A., Foit, K., Becker, J., Kaske, O., Paulsson, E., Peterson, M., Jernstedt, H., Kreuger, J., Schüürmann, G., Liess, M., 2017. Pesticides from wastewater treatment plant effluents affect invertebrate communities. Sci. Total Environ. 599-600, 387–399.

Murphy, D.J., Goggin, K., Paterson, R.R.M., 2021. Oil palm in the 2020s and beyond: challenges and solutions. CABI Agric. Biosci. 2 (1), 39.

Naghdi, M., Taheran, M., Brar, S.K., Kermanshahi-pour, A., Verma, M., Surampalli, R.Y., 2018. Removal of pharmaceutical compounds in water and wastewater using fungal oxidoreductase enzymes. Environ. Pollut. 234, 190–213.

Nair, R.B., Taherzadeh, M.J., 2016. Valorization of sugar-to-ethanol process waste vinasse: a novel biorefinery approach using edible ascomycetes filamentous fungi. Bioresour. Technol. 221, 469–476.

Näslund, J., Asker, N., Fick, J., Larsson, D.G.J., Norrgren, L., 2020. Naproxen affects multiple organs in fish but is still an environmentally better alternative to diclofenac. Aquat. Toxicol. 227, 105583.

Navina, B.K., Velmurugan, N.K., Senthil Kumar, P., Rangasamy, G., Palanivelu, J., Thamarai, P., Vickram, A.S., Saravanan, A., Shakoor, A., 2024. Fungal bioremediation approaches for the removal of toxic pollutants: mechanistic understanding for biorefinery applications. Chemosphere 350, 141123.

Negi, B.B., Das, C., 2023. Mycoremediation of wastewater, challenges, and current status: a review. Bioresour. Technol. Rep. 101409.

Nitayavardhana, S., Issarapayup, K., Pavasant, P., Khanal, S.K., 2013. Production of protein-rich fungal biomass in an airlift bioreactor using vinasse as substrate. Bioresour. Technol. 133, 301–306.

Nunes, B., Daniel, D., Canelas, G.G., Barros, J., Correia, A.T., 2020. Toxic effects of environmentally realistic concentrations of diclofenac in organisms from two distinct trophic levels, *Hediste diversicolor* and *Solea senegalensis*. Comp. Biochem. Physiol. Pt. C Toxicol. Pharmacol. 231, 108722.

Nwuche, C.O., Ogbonna, J.C., 2011. Isolation of lipase producing fungi from palm oil mill effluent (POME) dump sites at Nsukka. Braz. Arch. Biol. Technol. 54.

Olicón-Hernández, D.R., González-López, J., Aranda, E., 2017a. Overview on the biochemical potential of filamentous fungi to degrade pharmaceutical compounds. Front. Microbiol. 8.

Olicón-Hernández, D.R., González-López, J., Aranda, E., 2017b. Overview on the biochemical potential of filamentous fungi to degrade pharmaceutical compounds. Front. Microbiol. 8, 1792.

Omojasola, P.F., Adeniran, E.A., 2014. The production of itaconic acid from sweet potato peel using *Aspergillus niger* and *Aspergillus terreus*. Albanian J. Agric. Sci. 13 (4).

Papageorgiou, M., Kosma, C., Lambropoulou, D., 2016. Seasonal occurrence, removal, mass loading and environmental risk assessment of 55 pharmaceuticals and personal care products in a municipal wastewater treatment plant in Central Greece. Sci. Total Environ. 543, 547–569.

Palli, L., Spina, F., Varese, G.C., Vincenzi, M., Aragno, M., Arcangeli, G., Mucci, N., Santianni, D., Caffaz, S., Gori, R., 2019. Occurrence of selected pharmaceuticals in wastewater treatment plants of Tuscany: An effect-based approach to evaluate the potential environmental impact. Int. J. Hyg. Environ. Health 222 (4), 717–725.

Pallín, M.Á., González-Rodríguez, S., Eibes, G., López-Abelairas, M., Moreira, M.T., Lema, J.M., Lú-Chau, T.A., 2022. Towards industrial application of fungal pretreatment in 2G biorefinery: scale-up of solid-state fermentation of wheat straw. Biomass Convers. Biorefinery. 14 (1), 593–605.

Parchami, M., Ferreira, J.A., Taherzadeh, M.J., 2021. Starch and protein recovery from brewer's spent grain using hydrothermal pretreatment and their conversion to edible filamentous fungi — a brewery biorefinery concept. Bioresour. Technol. 337, 125409.
Pereira, C.R., Resende, J.T.V., Guerra, E.P., Lima, V.A., Martins, M.D., Knob, A., 2017. Enzymatic conversion of sweet potato granular starch into fermentable sugars: feasibility of sweet potato peel as alternative substrate for α-amylase production. Biocatal. Agric. Biotechnol. 11, 231–238.
Phonsiri, V., Choi, S., Nguyen, C., Tsai, Y.-L., Coss, R., Kurwadkar, S., 2019. Monitoring occurrence and removal of selected pharmaceuticals in two different wastewater treatment plants. SN Appl. Sci. 1 (7), 798.
Poh, P.E., Wu, T.Y., Lam, W.H., Poon, W.C., Lim, C.S., 2020. Waste Management in the Palm Oil Industry: Plantation and Milling Processes. Springer Nature.
Pokhrel, D., Viraraghavan, T., 2004. Treatment of pulp and paper mill wastewater—a review. Sci. Total Environ. 333 (1), 37–58.
Popli, S., Patel, U.D., 2015. Destruction of azo dyes by anaerobic–aerobic sequential biological treatment: a review. Int. J. Environ. Sci. Technol. 12 (1), 405–420.
Prasertsan, P., Binmaeil, H., 2018. Treatment of palm oil mill effluent by thermotolerant polymer-producing fungi. J. Water Environ. Technol. 16 (3), 127–137.
Premaratne, M., Nishshanka, G., Liyanaarachchi, V.C., Nimarshana, P.H.V., Ariyadasa, T. U., 2021. Bioremediation of textile dye wastewater using microalgae: current trends and future perspectives. J. Chem. Technol. Biotechnol. 96 (12), 3249–3258.
Pu, S., Ma, H., Deng, D., Xue, S., Zhu, R., Zhou, Y., Xiong, X., 2018. Isolation, identification, and characterization of an *Aspergillus niger* bioflocculant-producing strain using potato starch wastewater as nutrilite and its application. PLoS One 13 (1), e0190236.
Queiroz, M.I., Hornes, M.O., da Silva, Gonçalves, Manetti, A., Zepka, L.Q., Jacob-Lopes, E., 2013. Fish processing wastewater as a platform of the microalgal biorefineries. Biosyst. Eng. 115 (2), 195–202.
Rajwar, D., Paliwal, R., Rai, J.P.N., 2017. Biodegradation of pulp and paper mill effluent by co-culturing ascomycetous fungi in repeated batch process. Environ. Monit. Assess. 189 (9), 482.
Ramírez-Morales, D., Masís-Mora, M., Montiel-Mora, J.R., Cambronero-Heinrichs, J.C., Briceño- Guevara, S., Rojas-Sánchez, C.E., Méndez-Rivera, M., Arias-Mora, V., Tormo-Budowski, R., Brenes-Alfaro, L., Rodríguez-Rodríguez, C.E., 2020. Occurrence of pharmaceuticals, hazard assessment and ecotoxicological evaluation of wastewater treatment plants in Costa Rica. Sci. Total Environ. 746, 141200.
Requejo, A., Rodríguez, A., Colodette, J.L., Gomide, J.L., Jiménez, L., 2012. TCF bleaching sequence in kraft pulping of olive tree pruning residues. Bioresour. Technol. 117, 117–123.
Rezaei, R., Aghapour, A.A., Khorsandi, H., 2022. Investigating the biological degradation of the drug β-blocker atenolol from wastewater using the SBR. Biodegradation 33 (3), 267–281.
Riaño, B., Molinuevo, B., García-González, M.C., 2011. Treatment of fish processing wastewater with microalgae-containing microbiota. Bioresour. Technol. 102 (23), 10829–10833.
Robles, A., Lucas, R., de Cienfuegos, G.A., Gálvez, A., 2000. Biomass production and detoxification of wastewaters from the olive oil industry by strains of *Penicillium* isolated from wastewater disposal ponds. Bioresour. Technol. 74 (3), 217–221.
Rodriguez-Narvaez, O.M., Peralta-Hernandez, J.M., Goonetilleke, A., Bandala, E.R., 2017. Treatment technologies for emerging contaminants in water: a review. Chem. Eng. J. 323, 361–380.
Rousis, N.I., Zuccato, E., Castiglioni, S., 2017. Wastewater-based epidemiology to assess human exposure to pyrethroid pesticides. Environ. Int. 99, 213–220.
Rousta, N., 2023. Harnessing the potential of filamentous fungi for sustainable and healthy food system. In: Högskolan i Borås.
Rousta, N., Hellwig, C., Wainaina, S., Lukitawesa, L., Agnihotri, S., Rousta, K., Taherzadeh, M.J., 2021. Filamentous fungus *Aspergillus oryzae* for food: from submerged cultivation to fungal burgers and their sensory evaluation—a pilot study. Foods 10 (11), 2774.
Rousta, N., Aslan, M., Yesilcimen Akbas, M., Ozcan, F., Sar, T., Taherzadeh, M.J., 2023. Effects of fungal based bioactive compounds on human health. In: Critical Reviews in Food Science and Nutrition, pp. 1–24.
Rupani, P.F., Singh, R.P., Ibrahim, M.H., Esa, N., 2010. Review of current palm oil mill effluent (POME) treatment methods: vermicomposting as a sustainable practice. World Appl. Sci. J. 11 (1), 70–81.
Ryu, H., Ryu, H.W., Cho, K.-S., 2017. Characterization of dye decolorization in cell-free culture broth of *Trametes versicolor* CBR43. J. Microbiol. Biotechnol. 27 (1), 155–160.
Sainlez, M., Heyen, G., 2013. Comparison of supervised learning techniques for atmospheric pollutant monitoring in a Kraft pulp mill. J. Comput. Appl. Math. 246, 329–334.
Saleh, I.A., Zouari, N., Al-Ghouti, M.A., 2020. Removal of pesticides from water and wastewater: chemical, physical and biological treatment approaches. Environ. Technol. Innov. 19, 101026.
Samanta, K.K., Pandit, P., Samanta, P., Basak, S., 2019. 3 - Water consumption in textile processing and sustainable approaches for its conservation. In: Muthu, S.S. (Ed.), Water in Textiles and Fashion. Woodhead Publishing, pp. 41–59.
Sankaran, S., Khanal, S.K., Jasti, N., Jin, B., Pometto Iii, A.L., Van Leeuwen, J.H., 2010. Use of filamentous fungi for wastewater treatment and production of high value fungal byproducts: a review. Crit. Rev. Environ. Sci. Technol. 40 (5), 400–449.
Sar, T., Ferreira, J.A., Taherzadeh, M.J., 2020a. Bioprocessing strategies to increase the protein fraction of *Rhizopus oryzae* biomass using fish industry sidestreams. Waste Manag. 113, 261–269.
Sar, T., Ozturk, M., Taherzadeh, M.J., Ferreira, J.A., 2020b. New insights on protein recovery from olive oil mill wastewater through bioconversion with edible filamentous fungi. In: Processes, Vol. 8.
Sar, T., Ferreira, J.A., Taherzadeh, M.J., 2021a. Conversion of fish processing wastewater into fish feed ingredients through submerged cultivation of *Aspergillus oryzae*. Syst. Microbiol. Biomanuf. 1 (1), 100–110.
Sar, T., Harirchi, S., Ramezani, M., Bulkan, G., Akbas, M.Y., Pandey, A., Taherzadeh, M. J., 2021b. Potential utilization of dairy industries by-products and wastes through microbial processes: a critical review. Sci. Total Environ. 152253.
Sar, T., Larsson, K., Fristedt, R., Undeland, I., Taherzadeh, M.J., 2022. Demo-scale production of protein-rich fungal biomass from potato protein liquor for use as innovative food and feed products. Food Biosci. 47, 101637.
Satari, B., Karimi, K., Taherzadeh, M.J., Zamani, A., 2016. Co-production of fungal biomass derived constituents and ethanol from citrus wastes free sugars without auxiliary nutrients in airlift bioreactor. Int. J. Mol. Sci. 17 (3), 302.
Sharma, B., Tiwari, S., Bisht, N., Tewari, L., 2021. Eco-friendly bioprocess using agar plug immobilized *Penicillium crustosum* PWWS-6 biomass for treatment of wastewater contaminated with toxic Congo red dye for use in agriculture. Ind. Crop. Prod. 170, 113755.
Sharma, P., 2023. Industrial wastes as feedstock for filamentous fungi growth. In: Current Developments in Biotechnology and Bioengineering. Elsevier, pp. 181–196.
Sharma, P., Iqbal, H.M.N., Chandra, R., 2022. Evaluation of pollution parameters and toxic elements in wastewater of pulp and paper industries in India: a case study. Case Stud. Chem. Environ. Eng. 5, 100163.
Sheam, M.M., Biswas, S.K., Ahmed, K.R., Syed, S.B., Hossain, M.S., Khan, M.S.A., Hasan, M.R., Zohra, F.T., Rahman, M.M., 2021. Mycoremediation of reactive red HE7B dye by *Aspergillus salinarus* isolated from textile effluents. Curr. Res. Microb. Sci. 2, 100056.
Shete, B.S., Shinkar, N.P., 2013. Dairy industry wastewater sources, characteristics & its effects on environment. Int. J. Curr. Eng. Technol. 3 (5), 1611–1615.
Shojaee Nasirabadi, P., Saljoughi, E., Mousavi, S.M., 2016. Membrane processes used for removal of pharmaceuticals, hormones, endocrine disruptors and their metabolites from wastewaters: a review. Desalin. Water Treat. 57 (51), 24146–24175.
Singh, C., Vyas, D., 2021. Biodegradation by fungi for humans and plants nutrition. In: Biodegradation Technology of Organic and Inorganic Pollutants. IntechOpen.
Singh, G., Dwivedi, S.K., 2020. Decolorization and degradation of Direct Blue-1 (Azo dye) by newly isolated fungus *Aspergillus terreus* GS28, from sludge of carpet industry. Environ. Technol. Innov. 18, 100751.
Singh, H., 2006. Mycoremediation: Fungal Bioremediation. John Wiley & Sons.
Singh, S., Chandra, R., Patel, D.K., Reddy, M.M.K., Rai, V., 2008. Investigation of the biotransformation of pentachlorophenol and pulp paper mill effluent decolorisation by the bacterial strains in a mixed culture. Bioresour. Technol. 99 (13), 5703–5709.
Sinnaraprasat, S., Fongsatitkul, P., 2011. Optimal condition of Fenton's reagent to enhance the alcohol production from palm oil mill effluent (POME). Environ. Asia 4 (2), 9–16.
Souza Filho, P.F., Nair, R.B., Andersson, D., Lennartsson, P.R., Taherzadeh, M.J., 2018. Vegan-mycoprotein concentrate from pea-processing industry byproduct using edible filamentous fungi. Fungal Biol. Biotechnol. 5 (1), 5.
Souza Filho, P.F., Zamani, A., Taherzadeh, M.J., 2019. Edible protein production by filamentous fungi using starch plant wastewater. Waste Biomass Valoriz. 10 (9), 2487–2496.
Sperandio, G.B., Ferreira Filho, E.X., 2019. Fungal co-cultures in the lignocellulosic biorefinery context: a review. Int. Biodeterior. Biodegradation 142, 109–123.
Srivastava, A., Singh, P., Srivastava, S., Singh, S., 2023. Reclamation and characterization of value-added products from pulp and paper mill effluent using microbial fuel cell. In: Materials Today: Proceedings.
Strong, P.J., Burgess, J.E., 2008. Treatment methods for wine-related and distillery wastewaters: a review. Biorem. J. 12 (2), 70–87.
Subedi, B., Kannan, K., 2015. Occurrence and fate of select psychoactive pharmaceuticals and antihypertensives in two wastewater treatment plants in New York State, USA. Sci. Total Environ. 514, 273–280.
Sugiharto, A., 2018. Phytase production by fungi based on palm oil mill effluent. IOP Conf. Ser. Earth Environ. Sci. 166 (1), 012050.
Svensson, S.E., Bucuricova, L., Ferreira, J.A., Souza Filho, P.F., Taherzadeh, M.J., Zamani, A., 2021. Valorization of bread waste to a fiber-and protein-rich fungal biomass. Fermentation 7 (2), 91.
Świacka, K., Michnowska, A., Maculewicz, J., Caban, M., Smolarz, K., 2021. Toxic effects of NSAIDs in non-target species: a review from the perspective of the aquatic environment. Environ. Pollut. 273, 115891.
Szengyel, Z., Zacchi, G., 2000. Effect of acetic acid and furfural on cellulase production of *Trichoderma reesei* RUT C30. Appl. Biochem. Biotechnol. 89 (1), 31–42.
Taherzadeh, M.J., Fox, M., Hjorth, H., Edebo, L., 2003. Production of mycelium biomass and ethanol from paper pulp sulfite liquor by *Rhizopus oryzae*. Bioresour. Technol. 88 (3), 167–177.
Tan, Y.-A., 2006. By-products of palm oil extraction and refining. Oléagineux Corps Gras Lipides 13 (1), 9–11.
Taskila, S., Ahokas, M., Sotaniemi, V.-H., Mäki, M., Malinen, H.-L., Jaakkola, M., Virpiranta, H., Tanskanen, J., 2023. Conversion of Potato Peel Waste to Single Cell Protein by an Acidophilic Fungus.
Tay, J.-H., Show, K.-Y., Hung, Y.-T., 2004. Seafood processing wastewater treatment. In: Handbook of Industrial and Hazardous Wastes Treatment. CRC Press, pp. 706–749.
Telke, A.A., Kadam, A.A., Jagtap, S.S., Jadhav, J.P., Govindwar, S.P., 2010. Biochemical characterization and potential for textile dye degradation of blue laccase from *Aspergillus ochraceus* NCIM-1146. Biotechnol. Bioprocess Eng. 15, 696–703.

Thiebault, T., Boussafir, M., Le Milbeau, C., 2017. Occurrence and removal efficiency of pharmaceuticals in an urban wastewater treatment plant: mass balance, fate and consumption assessment. J. Environ. Chem. Eng. 5 (3), 2894–2902.
Toczyłowska-Mamińska, R., 2017. Limits and perspectives of pulp and paper industry wastewater treatment – a review. Renew. Sust. Energ. Rev. 78, 764–772.
Tran, N.H., Gin, K.Y.-H., 2017. Occurrence and removal of pharmaceuticals, hormones, personal care products, and endocrine disrupters in a full-scale water reclamation plant. Sci. Total Environ. 599-600, 1503–1516.
Trellu, C., Olvera Vargas, H., Mousset, E., Oturan, N., Oturan, M.A., 2021. Electrochemical technologies for the treatment of pesticides. Curr. Opin. Electrochem. 26, 100677.
Tung, T.Q., Miyata, N., Iwahori, K., 2004. Growth of *Aspergillus oryzae* during treatment of cassava starch processing wastewater with high content of suspended solids. J. Biosci. Bioeng. 97 (5), 329–335.
Uğurlu, M., Karaoğlu, M.H., 2009. Removal of AOX, total nitrogen and chlorinated lignin from bleached Kraft mill effluents by UV oxidation in the presence of hydrogen peroxide utilizing TiO_2 as photocatalyst. Environ. Sci. Pollut. Res. 16 (3), 265–273.
USDA, FASUDA, 2023. Palm Oil 2023 World Production. Vol. July.
Uyar, G.E.O., Uyar, B., 2023. Potato Peel Waste Fermentation by *Rhizopus oryzae* to Produce Lactic Acid and Ethanol.
Vasiliadou, I.A., Sánchez-Vázquez, R., Molina, R., Martínez, F., Melero, J.A., Bautista, L. F., Iglesias, J., Morales, G., 2016. Biological removal of pharmaceutical compounds using white-rot fungi with concomitant FAME production of the residual biomass. J. Environ. Manag. 180, 228–237.
Veiter, L., Rajamanickam, V., Herwig, C., 2018. The filamentous fungal pellet—relationship between morphology and productivity. Appl. Microbiol. Biotechnol. 102 (7), 2997–3006.
Velusamy, S., Roy, A., Sundaram, S., Kumar Mallick, T., 2021. A review on heavy metal ions and containing dyes removal through graphene oxide-based adsorption strategies for textile wastewater treatment. Chem. Rec. 21 (7), 1570–1610.
Vepsäläinen, M., Kivisaari, H., Pulliainen, M., Oikari, A., Sillanpää, M., 2011. Removal of toxic pollutants from pulp mill effluents by electrocoagulation. Sep. Purif. Technol. 81 (2), 141–150.
Vijayakumar, S., Manoharan, C., 2012. Treatment of dye industry effluent using free and immobilized cyanobacteria. J. Bioremed. Biodegr. 3 (10), 1–6.
Viuda-Martos, M., Fernandez-Lopez, J., Sayas-Barbera, E., Sendra, E., Perez-Alvarez, J. A., 2011. Physicochemical characterization of the orange juice waste water of a citrus by-product. J. Food Process. Preserv. 35 (2), 264–271.
Wang, S.-K., Yang, K.-X., Zhu, Y.-R., Zhu, X.-Y., Nie, D.-F., Jiao, N., Angelidaki, I., 2022. One-step co-cultivation and flocculation of microalgae with filamentous fungi to valorize starch wastewater into high-value biomass. Bioresour. Technol. 361, 127625.
Westlund, P., Yargeau, V., 2017. Investigation of the presence and endocrine activities of pesticides found in wastewater effluent using yeast-based bioassays. Sci. Total Environ. 607-608, 744–751.
Willetts, J.R.M., Ashbolt, N.J., 2000. Understanding anaerobic decolourisation of textile dye wastewater: mechanism and kinetics. Water Sci. Technol. 42 (1–2), 409–415.
Winker, M., Faika, D., Gulyas, H., Otterpohl, R., 2008. A comparison of human pharmaceutical concentrations in raw municipal wastewater and yellowwater. Sci. Total Environ. 399 (1), 96–104.
Wojcieszyńska, D., Guzik, U., 2020. Naproxen in the environment: its occurrence, toxicity to nontarget organisms and biodegradation. Appl. Microbiol. Biotechnol. 104 (5), 1849–1857.
Wojcieszyńska, D., Łagoda, K., Guzik, U., 2023. Diclofenac biodegradation by microorganisms and with immobilised systems—a review. Catalysts 13.
Wong, S.M., Zulkifli, M.Z.A., Nordin, D., Teow, Y.H., 2021. Synthesis of cellulose/nano-hydroxyapatite composite hydrogel absorbent for removal of heavy metal ions from palm oil mill effluents. J. Polym. Environ. 29 (12), 4106–4119.
Wonglertarak, W., Wichitsathian, B., Dararat, S., Yimratanabovorn, J., 2021. Evaluation of the biodegradability of tapioca starch wastewater by fungal treatment. Suranaree J. Sci. Technol. 28 (5).
Wu, J.-Y., Lay, C.-H., Chen, C.-C., Wu, S.-Y., 2017. Lipid accumulating microalgae cultivation in textile wastewater: environmental parameters optimization. J. Taiwan Inst. Chem. Eng. 79, 1–6.
Xiros, C., Vafiadi, C., Paschos, T., Christakopoulos, P., 2011. Toxicity tolerance of *Fusarium oxysporum* towards inhibitory compounds formed during pretreatment of lignocellulosic materials. J. Chem. Technol. Biotechnol. 86 (2), 223–230.
Yamuna, M., Meenakshi, R., Rajkumar, R., Rajesh, P., Selvam, K., 2017. Decolorization of AZO dyes and dye industry effluent by the screening of novel wood rot fungi. Int. J. ChemTech Res. 10 (10), 515–524.
Yan, Q., Gao, X., Chen, Y.-P., Peng, X.-Y., Zhang, Y.-X., Gan, X.-M., Zi, C.-F., Guo, J.-S., 2014. Occurrence, fate and ecotoxicological assessment of pharmaceutically active compounds in wastewater and sludge from wastewater treatment plants in Chongqing, the Three Gorges Reservoir Area. Sci. Total Environ. 470-471, 618–630.
Yaseen, D.A., Scholz, M., 2019. Textile dye wastewater characteristics and constituents of synthetic effluents: a critical review. Int. J. Environ. Sci. Technol. 16 (2), 1193–1226.
Yien Fang, T., Praveena, S.M., Aris, A.Z., Syed Ismail, S.N., Rasdi, I., 2019. Quantification of selected steroid hormones (17β-Estradiol and 17α-Ethynylestradiol) in wastewater treatment plants in Klang Valley (Malaysia). Chemosphere 215, 153–162.
Yinbo, Q., Xin, Z., Peiji, G., Zunong, W., 1991. Cellulase production from spent sulfite liquor and paper-mill waste fiber. Appl. Biochem. Biotechnol. 28 (1), 363–368.
Yustinah, Hidayat, N., Alamsyah, R., Roslan, A.M., Hermansyah, H., Gozan, M., 2019. Production of polyhydroxybutyrate from oil palm empty fruit bunch (OPEFB) hydrolysates by *Bacillus cereus suaeda* B-001. Biocatal. Agric. Biotechnol. 18, 101019.
Yusuf, F., Yakasai, H.M., Usman, S., Muhammad, J.B., Yaú, M., Jagaba, A.H., Shukor, M. Y., 2023. Dyes-decolorizing potential of fungi strain BUK_BCH_BTE1 locally isolated from textile industry effluents: characterization and LC-MS analysis of the metabolites. Case Stud. Chem. Environ. Eng. 8, 100453.
Zahi, M.R., Zam, W., El Hattab, M., 2022. State of knowledge on chemical, biological and nutritional properties of olive mill wastewater. Food Chem. 381, 132238.
Zainith, S., Purchase, D., Saratale, G.D., Ferreira, L.F.R., Bilal, M., Bharagava, R.N., 2019. Isolation and characterization of lignin-degrading bacterium *Bacillus aryabhattai* from pulp and paper mill wastewater and evaluation of its lignin-degrading potential. 3 Biotech 9 (3), 92.
Zhang, Z.Y., Jin, B., Bai, Z.H., Wang, X.Y., 2008. Production of fungal biomass protein using microfungi from winery wastewater treatment. Bioresour. Technol. 99 (9), 3871–3876.
Zhenying, S., Shijin, D., Xuejun, C., Yan, G., Junfeng, L., Hongyan, W., Zhang, S.X., 2009. Combined de-inking technology applied on laser printed paper. Chem. Eng. Process. Process Intensif. 48 (2), 587–591.