



## Review article

Bioremediation of waste by yeast strains <sup>☆</sup>

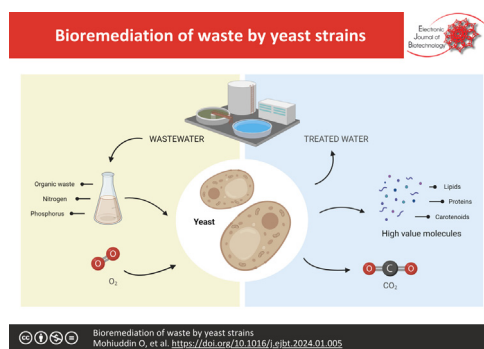
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## GRAPHICAL ABSTRACT



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## ABSTRACT

Over the past two decades, interest in pollutant removal by yeasts has grown substantially. Yeasts can remove high amounts of pollutants at low production costs under non-sterile conditions. This work presents a compilation of the studies carried out regarding the potential application of yeasts in the treatment of wastewater. For example, a summary is presented on data about various yeast strains that are used to treat wastewater. The study will help the decision-making process for the selection of yeast for a type of wastewater and support research efforts by acquiring an overview of advancements in this area. Yeast treatment is versatile and has outstanding adaptability to varying treatment conditions. The effectiveness of yeast in treating wastewater is influenced by multiple factors. Yeast technology could potentially be retrofitted to existing activated sludge processes or be used instead of bacteria. Within its characteristics, we can observe tolerance to low pH (3.0–5.0), high salinity, high organic loads, antibiotics, and survive in up to 12% v/v alcohol mixtures. In fact, using low pH for yeast cultivation reduces bacterial contamination and supports yeast domination under non-sterile conditions. Laboratory-scale trials for yeast wastewater treatment have shown improvement over the past two decades; however, efficiencies differ according to the type of wastewater. In general, yeast offers several benefits compared to traditional microbial treatment methods, especially in its capacity to effectively process diverse organic carbon sources. However, it still must be proven to be an effective technology at an industrial scale.

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## 1. Introduction

Water is socially, economically, and politically important. As our population increases, an alarming worldwide water shortage is being steered by high freshwater demand. According to the United Nations, every continent is already under threat of water scarcity. Currently, 1.2 billion people encounter water scarcity and 500 million more will confront it soon [1]. There is enough freshwater available in the world to fulfil the demands of its 7 billion people; however, freshwater resources are not evenly distributed [2]. Moreover, a significant quantity of water is not being appropriately used due to unsustainable management or accidental pollution from unavailable sanitation or wastewater treatment facilities [3]. It is also reported that groundwater is also being polluted because of untreated sewage release in developing countries [4]. This global water crisis is now pushing governing bodies to re-evaluate their consumption, operation and management of water resources notably as the global economy also depends on water availability [5]. To overcome the water shortage crisis, it has been suggested that secondary municipal effluent from wastewater treatment plants can be re-used [6]. Therefore, it is essential to develop sustainable and economically feasible water reclamation processes, with minimal environmental impact i.e. low energy, low greenhouse gas emissions and production of positive externalities [1]. Additional advantages of water reuse include the potential for returning nutrients and water to the soil, thereby aiding in the restoration of stream flows, providing support for agricultural activities, and revitalising aquatic ecosystems. However, reusing wastewater with inadequate treatment will pose a negative impact on the environment and human health [7]. Currently, most treatment plants use conventional processes such as the “activated sludge” process and trickle bed filters [8]. There is no doubt that these processes are effective in reducing organic pollutants. However, the effluent from conventional secondary treated wastewater contains significant concentrations of N and P. If discharged without further treatment, inorganic N and P can generate environmentally harmful microalgal blooms via eutrophication [9]. The microalgae blooms cover the water surface and prohibit oxygen transfer and sunlight to penetrate into anaerobic environments

resulting in an increased turbidity, odour, and death of desirable flora and fauna [10,11,12]. Therefore, additional steps must be applied to reduce pollutant levels to agreed emission standards [13,14,15]. At present, in the United Kingdom, the annual compliance limits for total P and N range from 1 to 2 mg.L<sup>-1</sup> and 10 to 15 mg.L<sup>-1</sup>, respectively [16]. The recovery of nutrients from secondary treated effluent especially N and P is being considered [17]. These resources are available in a few countries, energy-intensive [18] and mainly used for fertiliser production. Concerns are growing worldwide over the discharge of secondary treated effluent which contains large amount of phosphate [19].

The continuous development of sustainable, competent wastewater treatment technologies is essential. New systems can either be employed separately or retrofitted to conventional wastewater treatment plants in order to achieve the desired level of pollution reduction. Further treatment of secondary effluents is known as “advanced” or “tertiary” wastewater treatment, or “effluent polishing” [13]. To date, several biological and chemical approaches have been established for improved nutrient elimination such as nitrogen (N) and phosphorous (P). Nevertheless, only a few of them have the ability to reduce N and P concentrations simultaneously and in an effective manner [20]. Biological treatment using microorganisms was proposed by Oswald and Gotaas in 1957 [21] which included the use of photosynthetic organisms to fix the valuable nutrients in sewage wastewater. At the time, it was established to have a lower cost than chemical treatment. However, the operation of biological reactors still increases the total cost of a treatment plant [22]. Biological treatment has been used in various wastewater treatment processes, such as the treatment of municipal sewage, livestock wastes, fish farm waste and industrial wastes among others [18,23,24].

Yeast can be a potential candidate for either secondary or tertiary treatment. In secondary treatment, yeast actively competes with the combination of flocculated bacteria, fungi, protozoa, and rotifers present in the traditional activated sludge system. At the end of secondary treatment, yeast has an industrially proven settling capability for fast separation and the biomass produced can be valuable.

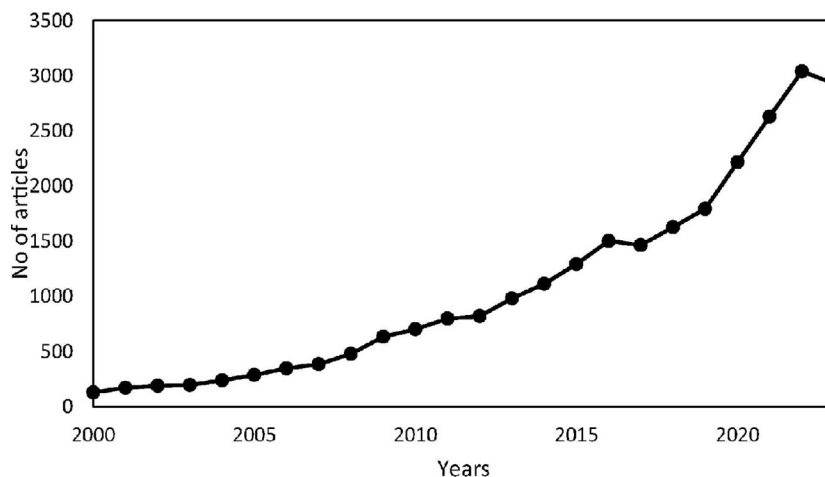


Fig. 1. Number of published papers annually related to yeast wastewater treatment.

For tertiary treatment, yeast competes with alternative physicochemical processes and biological (e.g. microalgae). Through photosynthesis, microalgae convert carbon dioxide into oxygen and use N and P to grow, thus producing valuable biomass. In comparison, yeast has a higher content of N and P in its biomass suggesting that it has a higher potential than microalgae.

To improve the efficiency and higher biomass production, co-culture of yeast with microalgae has been proposed. Velasquez-Orta et al. [25] discuss the intensification of yeast and microalgae in detail. When microalgae and yeast are cultivated, they form a symbiotic relationship. Yeast is a heterotrophic microorganism that requires oxygen to grow and produces carbon dioxide, while microalgae are able to consume CO<sub>2</sub> and produce oxygen. The co-culture of yeast with microalgae may reduce the stresses caused by dissolved oxygen on the growth of microalgae, as well as maintain the O<sub>2</sub>/CO<sub>2</sub> balance necessary for the growth of both species. There are also a number of complex sugars that yeast can break down into simple sugars, which can then be used by microalgae for energy [25].

The motivation of this study is to conduct an extensive literature review and summarise the performance and potential of yeast in wastewater treatment industries. To the best of our knowledge, the latest review on this field focused on yeast biomass production using wastewater [26]. Since then, many papers have been published on this topic improving the perspective on wastewater treatment. The study will help the decision-making process in the selection of yeast for a type of wastewater and support

research efforts by acquiring an overview of advancements in this area.

## 2. Yeast for wastewater treatment

Yeast can be grown in different cultivating media and can tolerate a wide range of operating conditions. For instance, there are species that can survive at very low pH, high concentrations of salt, organic and antibiotics [27], and some that can tolerate up to 12% alcohol by volume, which is toxic for most microorganisms [28]. The optimum pH for yeast growth is 3.0–5.0; however, they can still grow up to pH 7 [29]. Yeast rapid growth has made it interesting for biological studies. Yeast cell doubling time varies from 90 min to 140 min depending upon the type of medium used for cultivation [30]. Yeast ability to survive is outstanding as it has the adaptability to varying conditions [31].

Yeast is a unicellular microorganism that can be mass-produced at a relatively low cost [32]. The annual production of yeast worldwide is 2 million tonnes and is currently projected to increase year-on-year by approx. 4% [33]. According to Statista, the value of yeast product market worldwide in 2017 was 4.16 billion USD and is projected to increase to 8.94 billion USD in 2026 [34]. The production cost of yeast is around 6.714 to 7.286 USD per kg dry yeast [35]. Yeast is widely known for its applications in the food industries, particularly baking and brewing, but its full potential for wastewater treatment has not been fully explored. However, wastewater treatment by using yeast is now getting attention. According to the Scopus search results, the number of published articles based on “yeast wastewater treatment” has also increased from 129 published papers in 2023 to 2928 in 2023, as shown in Fig. 1.

The design of yeast wastewater treatment systems is similar to conventional wastewater treatment processes. They operate in open and aerobic conditions under acidic pH, and high salinity and can produce single-cell protein from wastewater [36]. Table 1 is a summary of the general advantages and disadvantages of using yeast in wastewater treatment systems.

Yeast treatment offers a variety of benefits including the capability to treat a broad range of organic waste. It can tolerate low pH levels, which minimises bacterial contamination, and allows yeast to dominate the culturing medium. The yeast can survive in non-sterile conditions. It also does not require sunlight to perform treatment activity. Yeast, however, has some disadvantages as well, such as the fact that it consumes oxygen and produces CO<sub>2</sub>. Yeast biomass can be contaminated by mould, it requires aer-

Table 1  
Summary of advantages and drawbacks of using yeast [37].

Advantages	Disadvantages
Can treat variety of wastes such as (oily and fatty complex organic compounds, organic acid, dyes, metallic waste, agricultural, industrial and refinery wastewater)	Consumes oxygen and produces CO <sub>2</sub>
Tolerance to low pH reduces bacterial contamination and supports yeast domination under non-sterile conditions	Low water pH would need adjustment and contamination by mould is not reduced.
Yeast does not require sunlight for growth and can grow aerobically	Energy requirement due to aeration and agitation
Can tolerate high salinity, antibiotics, and can survive in 12% alcohol by volume	Energy recovery from yeast biomass is still at a research phase

**Table 2**  
Growth of yeast cultivated under different wastewaters.

Strain	Type of wastewater	Max COD removal %	Temp °C	Biomass (g.L <sup>-1</sup> )	pH	Reference
<i>Rhodospiridium</i> sp.	Brewery effluent enriched with sugarcane molasses and urea	81.7	30	42.5	4	[40]
<i>Saccharomyces</i> sp.	Carbonated soft drinks (CSD) and nectars and juices (NJ)	65.4	30	5.6	5	[41]
<i>Saccharomyces</i> sp.	Soft drink wastewater	100	30	3.35	5	[42]
<i>Rhodotorula</i> sp.	Cassava wastewater	71.62	30	12.78	5.98	[43]
<i>Rhodotorula</i> sp.	Distillery wastewater	78.98	30	5.19	5.5	[44]
<i>Saccharomyces</i> sp.	Vegetable and fruit processing wastes	70	30	8.2	4.1	[45]
<i>Saccharomyces</i> sp.	Vegetable and fruit processing wastes	70	30	8.2	6.4	[45]
<i>Rhodotorula</i> sp.	Waste Glycerol Fraction and Potato Wastewater	83.2	26	23	10	[46]
<i>Trichosporon</i> sp.	Deproteinised potato wastewater	94.7	28.3	7.9	6.1	[47]
<i>Candida</i> sp.	Synthetic wastewater	100%	30	0.25	6.5	[39]

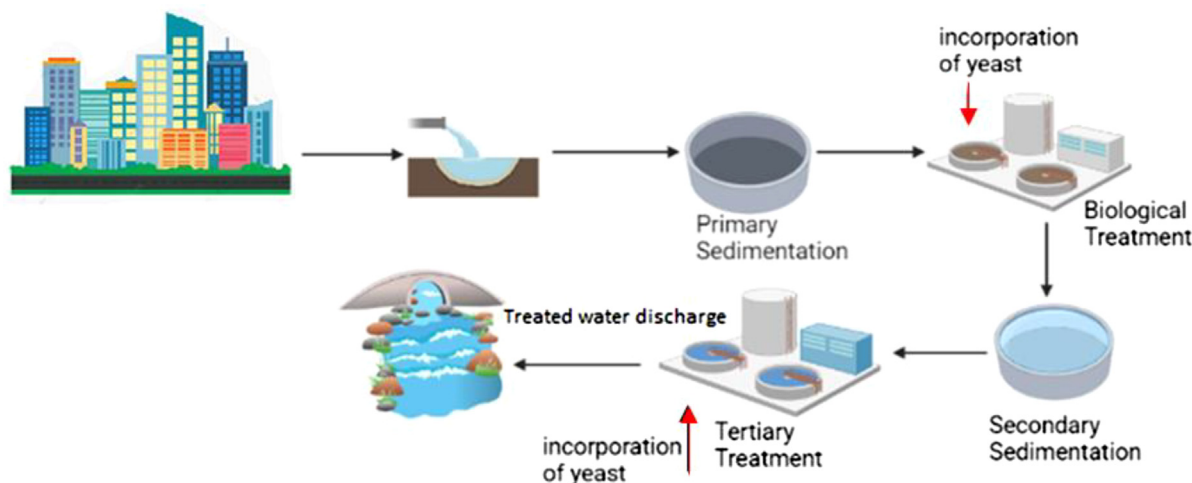
ation during treatment, and recovering valuable products from yeast biomass is still in the research phase. It has been proven that yeast can grow in domestic wastewater under non-sterile conditions [38]. Mohiuddin et al. [39] examine the performance of yeast in the secondary effluent and found that yeast can reduce 100% COD concentration within 24 h when the carbon concentration is less than 225 mg.L<sup>-1</sup>. Table 2 shows results for yeast COD removal efficiency and biomass production at different initial conditions. In general, yeast can achieve 70–100% COD removal depending upon the type of yeast, type of medium and operational condition. Despite the same medium, every yeast strain exhibits a different maximum specific growth rate and produces different biomass yields.

### 3. Yeast vs current microbial technologies for wastewater treatment

#### 3.1. Secondary treatment

Conventional Activated Sludge (CAS) is the most widely used wastewater treatment approach to treat municipal and numerous industrial wastewaters. Mixture of microorganisms such as bacteria, fungi, protozoa, and rotifers degrade organic substrate and nutrients using oxygen, resulting in a significant decrease in pollutant concentration [48,49]. However, due to aeration requirements, it is energy-intensive [50]. The energy consumption of wastewater treatment plant varies with the plant size, type of treatment plant and degree of pollutants [51]. Velasquez-Orta et al. [52] investigated the energy consumption and carbon production with perspective of treatment plant infrastructure. Data were collected from 87 different wastewater treatment plants (16 activated

sludge and 71 biofilter plants) and 196 pump stations in four counties of Northeast England. Studies show that AS plant consumed significantly more energy because of aeration and produced more CO<sub>2</sub> emissions: approx. 0.4 kWh.m<sup>-3</sup> and 0.4 kg.m<sup>-3</sup> respectively [52]. In a typical wastewater treatment, plant-activated sludge aeration consumes approx. 56% of the total energy [53]. Replacing bacteria with yeast in the activated sludge process offers numerous benefits. The inclusion of yeast can significantly decrease the oxygen demand, requiring only 60% of the amount needed in a conventional activated sludge (CAS) system. This is due to the efficient oxygen diffusion facilitated by the net-structure of yeast flocs, eliminating the need for excessive dissolved oxygen supplementation in the water. Hence, yeast treatment capacity is 3–5 times higher in comparison with CAS [27]. When compared to bacteria, yeast-based treatment generates a substantial quantity of biomass that can be utilised either for biofuel production due to its elevated lipid content or as animal feed owing to its high protein content. The yeast forms a floc that settles easier than bacteria because it is larger than them [54]. A study was conducted to investigate yeast dominance in bacterial-yeast-activated sludge with high organic load and acidic pH. Seed sludge had 2% yeast and 98% bacteria. By lowering the pH from 6.5 to 7.5 to 5.0–6.0, bacterial cell levels dropped to 46% from 98%, while yeast cells increased to 54%. When the pH was further lowered to 4.0–5.0, the yeast population rose to 88%, while the bacteria population declined to 12%. Therefore, it is proposed that acidic pH levels will suffice in batch mode to produce yeast-dominated sludge communities. However, an acidic pH with a high organic load is necessary for yeast superiority in activated sludge during continuous operation mode [29]. According to Han et al. [55], it was proposed that yeast growth is favoured by a lower pH, whereas the inhibitory sub-



**Fig. 2.** Overview of main wastewater treatment processes indicating the process where yeast can be incorporated.

stances released by yeast hinder the growth of bacteria. Another advantage of yeast treatment over the CAS approach is that it can treat oily wastewater while the conventional approach requires pre-treatment of oil and greases. The utilisation of yeast for treatment purposes eliminates the need for constructing new treatment facilities, as it can be seamlessly integrated into existing activated sludge processes and can serve as a substitute for bacteria as shown in Fig. 2.

### 3.2. Tertiary treatment

After the secondary treatment stage, tertiary treatment is required in order to reduce the pollutant concentration to the standard limits. One of the emerging approaches for the tertiary treatment is by using either by using microalgae or yeast. Microalgae treatment can further reduce inorganic N and P concentrations [56]. Microalgae offers a cost-effective approach to removing nutrients from secondary effluent [25]. It has a high capacity for inorganic nutrient uptake [57]. Microalgae can be grown in autotrophic, heterotrophic or mixotrophic condition; however, it is generally cultivated in autotrophic condition, where solar energy or artificial light helps the microalgae to consume N and P, thus producing valuable biomass and converting CO<sub>2</sub> into O<sub>2</sub>. Microalgae also has the capability to uptake heavy metals from wastewater [22]. Yeast can also compete with microalgae as it also has a rapid growth rate, and its cultivation is also not affected by light intensity and photoperiod [58]. Typically, microalgae N content is 6% and P content is 0.87% [59] whereas yeast N content is 10% and P content is 3–5% [60]. This suggests that, in terms of N and P composition, yeast is richer than microalgae, and therefore, it could be estimated that yeast may require more N and P for growth as compared to microalgae.

## 4. High organic loads wastewater treatment

Yeast treatment reduces organic contaminants from the cultivation medium, which saves energy and time by reducing pre-treatment steps [61]. Yeast can metabolise various carbon substrates such as hydrocarbons, fatty acids and organic acids [37,62]. Thus, yeast has been used to treat industrial wastewater and was able to reduce pollutants by up to 60% [63]. Yeast consumes organic acid, increasing pH to neutral under aerobic conditions, when there is organic acid present in the culturing medium [64]. This reduces wastewater treatment expenditure and supports an additional treatment process such as an activated sludge process for supplementary treatment. As a result, yeast treatment seems to be better suitable for treating acids, oily, high salinity, ammonia, wastewater containing significant amounts of organic compounds, or industrial wastewater that are not suitable for anaerobic treatment [26].

Yeast utilises carbon sequentially when there are multiple sources of carbon present in the medium [65]. To utilise multi-source carbon simultaneously and efficiently, mixed cultures have been suggested [66]. For instance, results from the mono-culture of *Kluyveromyces marxianus* and mixed culture of *Kluyveromyces marxianus* and *Candida krisei* were compared for the removal of total COD from cheese whey fermentation. Since Whey has multiple carbon sources; therefore, mixed culture has the 8.8% higher COD removal efficiency [67]. In non-sterile heterotrophic conditions, wild yeast and microalgae consortia have successfully achieved high nutrient removal rates in municipal wastewater [38]. Two yeast strains, *Candida tropicalis* and *Trichosporon asahii*, were isolated from refinery wastewater. These yeast strains were able to improve adaptation mechanisms to stay alive in the refinery wastewater. A direct relation was discovered between

hydrophobicity of the yeast and the biodegradation of the crude oil. Interestingly, both strains exhibit efficient crude oil degradation, including faster growth on aliphatic hydrocarbons, and can metabolise all n-alkanes, but they are unable to degrade all aromatic hydrocarbons [68].

The Low Coal Wastewater (LCWW) was treated in three phases over the course of 170 d using continuous anaerobic membrane bioreactors. Phase 1 duration was from 0 to 50 d with LCWW alone, phase 2 duration was from day 50 to 100 with the addition of glucose, and phase 3 duration was from day 100 to day 170 with the addition of yeast waste obtained as a co-substrate. The amount of COD in the first phase decreased slightly whereas no CH<sub>4</sub> was produced. CH<sub>4</sub> production started in phase two and reached 106 mL.day<sup>-1</sup>, while the COD removal efficiency improved to 31%. When yeast waste was added to the medium as a co-substrate, the highest amount of CH<sub>4</sub> was produced (361 mL CH<sub>4</sub>.day<sup>-1</sup>) and COD was removed (58%). Yeast as a substrate improved coal degradation, resulting in more CH<sub>4</sub> production and reduced COD content [69]. Yeast was added as an inoculum to treat landfill leachate using a membrane bioreactor (MBR). This yeast-MBR achieved significant COD, colour, ammonia, and humic substance removals, of 68%, 79%, 68%, and 50%, respectively. However, there was severe contamination by wild filamentous fungi and bacteria in the yeast-MBR. It is believed that these contaminations also contributed to the degradation of organic matter; however, this could not be quantified [70].

In summary, yeast treatment emerges as a versatile and effective approach for reducing high organic loads that are difficult to remove in conventional wastewater treatment, such as hydrocarbons and salinity. It can also help minimise the need for extensive pre-treatment steps. Overall, the diverse capabilities of yeast in treating various types of industrial wastewater underscore its importance as a sustainable and adaptable solution, contributing to the ongoing efforts in efficient and environmentally friendly wastewater management.

### 4.1. Carbohydrates

The food processing and fermentation industries widely produce carbohydrate-rich wastewater. This wastewater can act as a raw material to produce single-cell protein using a bioconversion process. It was found that the pH of the medium is an important parameter to be considered for the biodegradation of complex carbohydrates during the treatment process. Fermentation converts carbohydrates to organic acids decreasing pH below the optimum range of 4.6–6.5. This decrease in pH could prevent the oxidation reaction of Tricarboxylic-Acid Cycle (TCA), affecting the COD removal efficiency. It was suggested that pH manipulation may be required in high carbohydrate wastewater treatment [71]. Yeast has been effectively utilised in the treatment of wastewater originating from vegetable processing industries, including the treatment of water extracted from cabbage, watermelon, and the residual biomass derived from salads and tropical fruits [45,72], pineapple cannery waste [73,74], silage effluent [75] and bamboo waste [76]. Brewery wastewater contains a high amount of sugar as the potential carbon source, hence, can also be treated by yeast [77]. Wastewater from butanol fermentation has been treated via *Trichosporon dermatis* without any pre-treatment or nutrient addition. After five days, 68% of COD was removed with significantly high biomass (7.4 g.L<sup>-1</sup>), in which 13.5% lipid content were present [78]. Tequila distillery wastewater was also treated with *R. glutinis* and *C. curvatus*. After 144 h of biological treatment, the COD removal was 79% by *R. glutinis* and 84% by *C. curvatus*. It has been shown that when growth slows down, COD removal rates also decrease [44]. *Candida utilis* was cultivated in potato wastewater and glycerol. This investigation shows that the reductions in glycol

erol, nitrogen, and COD were, 83%, 51%, and 91%, respectively, whereas COD index value decreased by 74% when only potato wastewater was used as a cultivation medium [47]. *Rhodotorula glutinis* were grown in cassava wastewater with and without additional supplements. Results showed that there is no need to provide an additional supplement to cultivate yeast in cassava wastewater, as it has all the necessary essential micro- and macronutrients [43]. The soft drinks industries consume large quantities of water. In the beverage industry, wastewater consists of rejected products (because of lack of carbonation, poor flavour, or packaging defects) and returned products (unsold before the expiry date). A laboratory scale study has shown that returned soft drink products are rich in sugar content, which makes them appropriate for the cultivation of yeast. However, other nutrient supplements must be provided [42]. The pH of waste carbonated soft drinks and waste juices is acidic (pH 2.5–3.8), which decreases the chances of bacteria growth, and favours yeast growth [79]. A soft drink/whey mixture was treated with baker's yeast and the COD removal rate was 63% after 28 h, 25% higher removal than for the soft drink nectar juice mixture [41]. Recently, sugarcane molasses was added to secondary brewery wastewater and treated with red yeast *Rhodospiridium toruloides* NCYC921. Urea was added because the medium exhibited nitrogen-limiting conditions. After the first batch, nitrogen, COD, and sugar removals were 46%, 82% and 100%, respectively. After cultivation, 100% phosphorus removal was observed [40].

In summary, the treatment of carbohydrate-rich wastewater from various industries using yeast-based bioconversion processes has shown >90% COD and P removals. Yeast presents a versatile solution for the treatment of carbohydrate-rich wastewater generated by food processing and fermentation industries. These findings feature the potential of yeast-based processes for sustainable and effective treatment of carbohydrate-rich industrial wastewater.

#### 4.2. Oils

The food processing industries are water-intensive and produce a significant quantity of oil-rich wastewater. For instance, typically one tonne of olives produces one/two tonnes of oil-rich wastewater. In a continuous process, processing 1 kg of olives requires 21 kg of water [80]. The olive mill effluent has BOD ranges from 12,000–63,000 mg.L<sup>-1</sup> and COD values from 80,000–200,000 mg.L<sup>-1</sup> [81]; 200 to 400 times higher than municipal sewage. The discharged wastewater from the vegetable oil industries has considerable effects on the environment as conventional processes such as dissolved air flotation (DAF), flocculation, demulsification remove only part of the contaminants and are energy-consuming [82,83].

Yeast is effective in reducing the oil content of culture media [84]. The effluent from olive mills usually does not have enough nitrogen, phosphorus, and sulphate for satisfactory aerobic purification. Hence, yeast treatment was studied for olive mill effluent alone, and with nitrogen, phosphorus, and sulphate by using three different yeast *Aspergillus sp.*, *Geotrichum sp.*, and *Candida tropicalis*. The COD removal of olive mill effluent wastewater was too low, compared to olive mill effluent with nutrients, nitrogen, phosphorus and sulphate. Therefore, for aerobic degradation of oil-rich medium, additional nutrients must be supplied if not present in wastewater [85]. Wastewater from soybean oil manufacturing, with, over hexane extract of 10,000 mg.L<sup>-1</sup>, was directly treated using nine strains of yeast; all of them were capable of decomposing oil. No pre-treatment steps were involved, but the effluent concentration was reduced to 100 mg.L<sup>-1</sup> of oil over a one-year pilot plant operation [84]. *Trichosporon fermentans* were also found useful in degrading soybean industries' wastewater containing oils and fats that are challenging to reduce by conventional biological

technologies. When the wastewater treatment process was finished, a hot buffer solution was used to strip off the residual oil absorbed on the surface of yeast. Interestingly, it was found that only 0.5% of removed oil was remaining on the surface of yeast and the remaining was utilised by yeast for growth [86].

*Candida utilis* demonstrates the highest rate of oil uptake and the highest specific growth rate (compared to other yeast including *Rhodotorula rubra*, *Trichosporon cutaneum* and *Candida boidinii*). It was also found that the initial N:C ratio affects the oil degradation efficiency, biomass production and protein content. Higher initial N:C ratio decreases the oil degradation efficiency but increases the protein content [87]. Ten yeast strains that were capable of consuming vegetable oil or related compounds were used to treat wastewater with 15 g.L<sup>-1</sup> COD and 10 g.L<sup>-1</sup> oil, on average. The COD and oil reduction were >89% and >99%, respectively [88]. A coculture of two strains, ST3411 and ST3412, efficiently degraded oil even at 20°C, pH 7, and low content of nitrogen and phosphorus [89]. The effect of adding nitrogen on the treatment of wastewater from salad oil manufacturing has been studied. The results show that when COD:N values were between 50:1 and 20:1, the sludge settleability was improved and the oil removal rates were above 90% [90]. In addition, yeast's capacity to emulsify was found to be a critical parameter in determining its suitability for handling vegetable oil manufacturing wastewater. The reason is that it can facilitate the uptake of contaminants that are hydrophobic [88]. Wastewater with a high concentration of lipids (10 g.L<sup>-1</sup>) was treated with *Bukholderia sp.* DW2-1 effectively reduces lipid content to 1.8 g.L<sup>-1</sup> in 24 h [91]. Recently, *M. capitatus* JT5 was grown in undiluted and diluted olive mill wastewater (OMW) with YEP (yeast extract 2% and peptone 2%) under control conditions. Results show that the growth rate of *M. capitatus* JT5 in YEP was 0.143 h<sup>-1</sup>. When 10%, 25%, and 50% OMW were added into the YEP medium, the growth rate increased to 0.182, 0.344 and 0.382 h<sup>-1</sup>. However, when 75% OMW with YEP and alone 100% OWM were used as a medium, the specific growth rate decreased to 0.309 h<sup>-1</sup> and 0.248 h<sup>-1</sup>.

When 10%, 25%, 50%, and 75% OMW were added, the growth rates increased significantly. However, 100% of OMW exhibited a lower growth rate than 25% OMW. Salgado et al. [92] suggested that recalcitrance of OMW (high concentration of polyphenols) had a negative effect on the growth profile.

Recently, a hybrid system incorporating dissolved air flotation (DAF), a yeast bioreactor, an up-flow anaerobic sludge blanket reactor and a biological aerated filter was used to treat oilfield wastewater. At optimised settings, DAF treated the majority of the oil content, and the rest of the oil was efficiently degraded by yeast in the bioreactor. The overall COD and oil removal efficiency were 96% and 99.6%, respectively [93].

Antibiotic waste can have a high oil content and has been pre-treated by yeast-based sequencing batch reactor. This was optimised in a pilot plant and later applied to the pharmaceutical factory on a full-scale project. Both pilot plant and full-scale pre-treatments demonstrated high-level oil removal rates and outstanding sludge settling velocity with the dominance of yeast on bacteria [94].

Conventional treatment methods are often insufficient, leading to the exploration of yeast-based approaches. Yeast emerges as a pivotal player in the effective treatment of wastewater from oil-rich industrial processes, particularly in the food processing and vegetable oil industries. Yeast proves that it could be used as a sustainable and efficient oil-rich wastewater remediation. In conclusion, the highlighted studies collectively underscore yeast's pivotal role in achieving high-level oil removal rates, outstanding sludge settling velocity, and overall superior efficiency in the treatment of oil-rich wastewater. The multifaceted contributions of yeast position it as a key component in sustainable and effective

wastewater treatment strategies for industries grappling with oil-rich effluents.

#### 4.3. Dairy

In dairy wastewater, there can be a significant variation in the concentration of pollutants [95]. Wastewater discharges from dairy industries are frequently sporadic, and their properties vary across different dairy plants, influenced by the specific operational procedures implemented at each facility [96]. Dairy wastewater treatment can be challenging due to fat levels [97]. During aerobic wastewater treatment, fats block oxygen transfer. They can also freeze at lower temperatures, preventing flow and causing unpleasant odours in anaerobic wastewater treatment. Some yeast produce sophorolipid, a biosurfactant that facilitates the solubilisation of fats and oils in an aqueous phase that can then be consumed, reducing COD [98]. It was found that when the production of sophorolipid is below the detectable limit, the COD removal rate is not satisfactory. Therefore, it has been suggested to add supplements that could support yeast growth. Supplements such as sugarcane molasses (1%) and yeast extract (0.1%) were added to a synthetic wastewater containing fats. The fats were completely removed in 96 h. It was found that 1–2 g.L<sup>-1</sup> of sophorolipids was enough to fully solubilise these fats in wastewater [99]. Dairy wastewater containing high COD, fats and oil were treated with biosurfactant production yeast *Candida bombicola*. To support yeast growth, sugarcane molasses (1% w/v) and yeast extract (0.1% w/v) were added to the wastewater. *C. bombicola* achieved more than 95% COD removal in batch and continuous operation, thus, a pre-treatment stage to eliminate fats and oils was not required [98]. Daverey et al. [100] used glucose, yeast extract and soybean oil as the additional supplement for dairy wastewater. The supplements assisted the production of biosurfactant (62 g.L<sup>-1</sup> sophorolipids) and the removal of COD. The biosurfactant produced by yeast was highly active over a wide pH range between 2 and 10 with the highest activity at pH 6 [100]. Twenty-seven strains of yeast were tested for the decomposition of milk fat at various temperatures over a three-week period, and it was found that all 27 strains were able to decompose milk fat; however, the degradation was dependent on temperature [101].

In conclusion, yeast represents a fundamental alternative to address the unique challenges posed by dairy wastewater treatment. Yeast's capacity to produce biosurfactants, particularly sophorolipids, presents a sustainable and efficient approach to solve the challenges associated with fats in dairy wastewater. The supplementation of nutrients to support yeast growth, coupled with the broad pH range of biosurfactant activity, underscores the adaptability and effectiveness of yeast in diverse dairy wastewater treatment scenarios.

#### 5. High-salinity wastewater treatment

The food processing industries, particularly the vegetable and seafood industries, generate massive volumes of briny waste that has significant amounts of organic pollutants. Because of high salinity, these wastes are not easily treatable through biological approaches [102]. In a conventional biological system, low BOD removal has been observed because of the plasmolysis of organisms [103]. Due to the elevated salinity, there is an escalation in osmotic pressure between the protoplasm and the surrounding high-saline environment. As a result, dehydration occurs, which in turn results in cell breakdown, leading to substantial inhibition of bacterial growth [104]. The process of decreasing salt concentration through ion-exchange methods or reverse osmosis prior to biological treatment is a considerably costly endeavour [105].

Research shows that yeast can produce a much better result than bacterial cultures when it comes to treating high-salinity organic wastewater. At low salt concentration, bacterial cultures performed more efficiently. Out of 70 isolated yeast, *Pichia guilliermondii* A9 was selected to cultivate in brine wastewater from a kimchi factory. The BOD of the medium decreases by up to 90% within 24 h. It was found that at 10% (w/v) NaCl, the growth was not inhibited and reduced drastically at a concentration greater than 12% (w/v) NaCl [106]. Recently, it was found that yeast is capable of treating wastewater with salinity up to 120 g.L<sup>-1</sup> NaCl [107].

This research highlights the potential of yeast as a robust biological agent for addressing the challenges posed by high-salinity organic pollutants (Up to 120 g.L<sup>-1</sup> NaCl) in food processing wastewater, providing a sustainable and efficient alternative to conventional methods such as reverse osmosis that high operational cost for salt concentration reduction processes. The findings open avenues for yeast-based approaches in addressing the environmental impact of high-salinity wastewater from food processing industries.

#### 6. Removal of heavy metals from wastewater

Metals are necessary minerals for aerobic and anaerobic organisms. As a result, heavy metals can significantly harm human health. Heavy metals have a tendency to accumulate within internal organs, as the body is unable to process heavy metals, therefore, leading to severe health issues [108]. Many industries such as electroplating, metal finishing, textile, storage batteries, and mining produce wastewater that contains high concentrations of heavy metals, causing serious ecological harms and potential threats to human wellbeing [109]. Metal accumulative bioprocesses can be divided into two classifications: bioaccumulation by growing cells of biomass or biosorption uptake by dead biomass. The benefits of using dead cells are that they are not affected by toxic waste, have no need to provide nutrients, can be reused for numerous process cycles and can be stored at room temperature for a prolonged duration. The dead cells collect heavy metal ions to a similar or higher degree than live cells. Unlike certain inorganic adsorbents that may require chemical synthesis or activation, yeasts operate without the need for additional chemical treatments. The efficiency of metal ion accumulation by dead cells depends on the technique used to kill the cells. There are physical approaches such as heat treatment or drying, and chemical methods such as caustic, organic, or acidic treatment. Experiment shows that yeast biomass can remove heavy metal ions by a similar adsorption and absorption mechanism as other microbial biomass [110].

The role of several functional groups in the *Aspergillus niger* cell wall was examined during the biosorption of lead, cadmium, and copper [111]. It was found that carboxylate and amine groups had a significant effect on metal ion biosorption, whereas the phosphate groups and lipid fraction did not perform any key role in the biosorption of metal ions. Biosorption occurs as a result of the ion-exchange process while displacing Ca<sup>2+</sup>, Mg<sup>2+</sup> and K<sup>+</sup> ions on the biomass surface [111]. *Streptomyces rimosus* dead biomass was found to be an efficient adsorbent of Pb<sup>2+</sup> in dilute solutions if pre-treated with NaOH. Each gram of pre-treated biomass can obtain up to 135 mg of lead [112]. Waste beer yeast is a low-cost adsorbent for adsorbing copper and lead ions from wastewater. Investigations have shown that its effect is affected by pH, temperature, contact time and adsorbent dose. Adsorption by waste beer yeast was simultaneously and spontaneously for copper and lead ions [109]. Some other studies also suggest that residual biomass from yeast fermentation can biosorb heavy metals [113,114,115]. Recently, a comparative study has been performed between yeast

*Saccharomyces* sp. and fungi *Aspergillus* sp. for the biosorption of platinum and palladium. The biosorption process was fast as equilibrium was reached in less than 45 min. Results show that fungi had a higher adsorption capacity for both metals than yeast [116].

Immobilised *Saccharomyces cerevisiae* biomass has been shown to use a chemical sorption mechanism for the sorption of platinum. There was a fast initial sorption showing 70% of metal reduction in 5 min and reaching 82% within 20 min when the platinum solution concentration was 50 mg.L<sup>-1</sup>. When the initial concentration was increased to 200 mg.L<sup>-1</sup>, the removal efficiency of platinum decreased to 72%. [117].

The waste brewer's yeast was used to functionalise a bentonite surface which acts as bed support. The optimum condition was, 100 mg of yeast-functionalised bentonite, 2 mg.L<sup>-1</sup> of Pt(IV), at 2 pH for the time of 180 min, which had an adsorbent efficiency of 95.8% [118]. In recent research, investigations utilising both wild-type yeast and genetically modified yeast strains have been conducted for the removal of heavy metals. These studies underscore the promising capability of yeast in the field of metal bioremediation [119]. Overall, the findings highlight the potential of yeast biomass in diverse forms as effective biosorbents for heavy metal removal, offering valuable insights for sustainable wastewater treatment practices.

### 7. Decolourisation of wastewater

Synthetic dyes are essential ingredients in the textile industrial application. Apparently, 10% of dyes produced annually make their way into natural water bodies [120] and affect photosynthetic activity in aquatic life due to reduced light penetration [121]. Yeast rapid growth and resilience in challenging environmental conditions, such as low pH levels, make them a viable substitute for bacteria in the purification of water contaminated with dyes [122]. Yeast has ion-exchange properties because the cell wall of yeast is comprised of polysaccharides, as a basic unit of the cell wall, plus proteins and lipids, which provide diversity in functional groups,

capable of binding dye molecules. Because of the range of functional groups across species of yeast, the affinity and specificity for dye-binding differ significantly [123]. It has also been suggested that different culture conditions could alter the establishment of these groups and hence change the metal uptake characteristic of yeast [115].

Yeast can remove dyes either via biosorption or through biodegradation. Brewery waste yeast was found to be capable of removing the anionic dye Acid Orange 7 (AO7) which is used in the textile industry. It can be an effective biosorbent for wastewater treatment and is economical to use as it is abundantly available [124]. The efficiency of dye removal is influenced by pH, with the highest biosorption occurring at a pH of 2.0 [124].

In one study, 2402 strains of yeast were isolated from various sources. Among them, only 30 strains showed melanoidin pigment decolourisation on solid media. It was *Issatchenka orientalis* (SF9-246) which exhibited both adsorption and degradation abilities and showed the greatest decolourisation efficiency of approximately 60%. It reduced melanoidin pigment by 91% with COD and BOD removal of 80% and 77%, respectively, at 30°C and pH 5.0 over a 7-day batch culture in the anaerobic treatment of molasses wastewater. During 3 replacement cycles, this strain delivered a constant decolourisation yield of 70% [125]. WR-43-6 *Citeromyces* sp. which was isolated from 205 yeast strains demonstrated the highest decolourisation yield, of 69%, at 30°C for 8 d in a molasses pigment solution [126].

On this basis, the biomass of thermotolerant ethanol-producing yeast strain *Kkuyveromyces marxianus* IMB3 which has a high affinity for heavy metals was used for biosorption isotherm analysis on textile dyes. Each gram of biomass biosorb 98, 68 and 37 mg of Remazol Turquoise blue, Remazol Red and Remazol Black B, respectively, when the dye concentration was more than 100 mg.L<sup>-1</sup> [127].

The rate of absorbance was shown to be dependent on the availability of the active sites on the surface of the yeast. Adsorption occurs more rapidly and is more intense during the transient phase

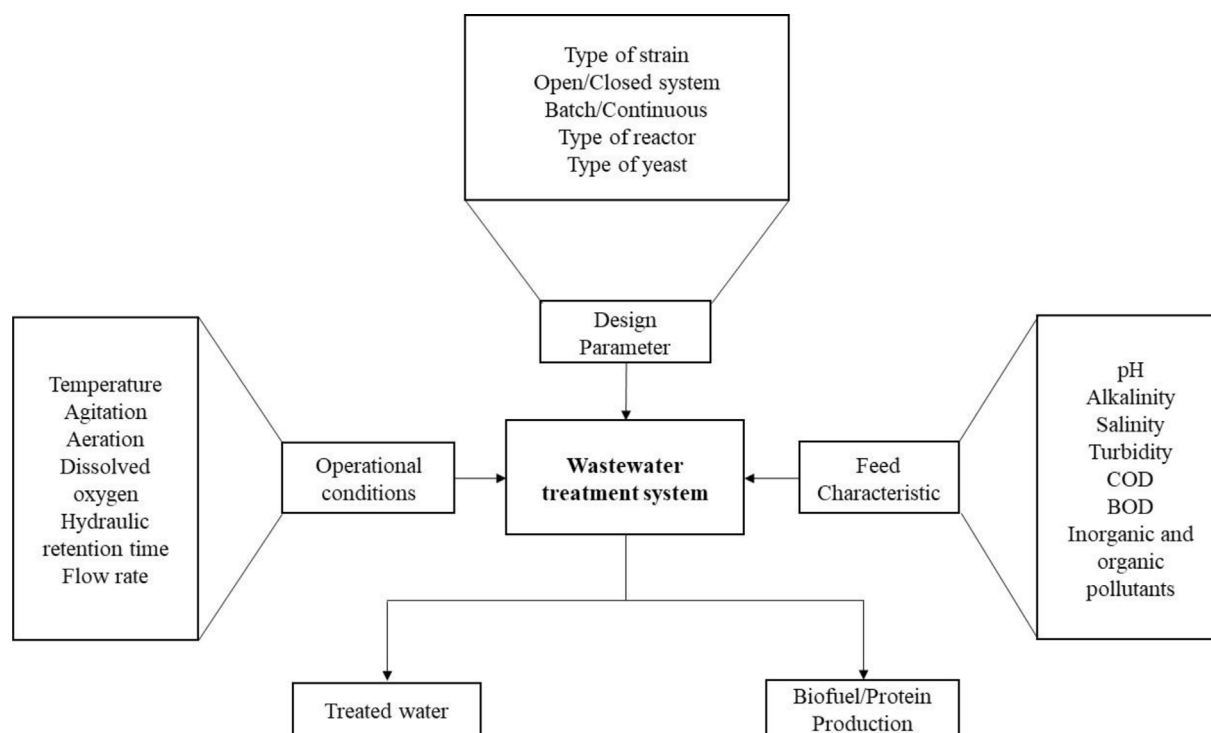


Fig. 3. Variables to consider for a yeast wastewater treatment systems.

when the adsorbent is in contact with the dye. This is because of the availability of the active sites on the surface of the adsorbent. Afterwards, the stationary phase develops where the adsorption is slow due to fewer accessible active sites. Finally, equilibrium is achieved when most of the available sites are occupied by dye molecules [128].

Yeast, with its rapid growth and resilience in challenging environmental conditions, proves to be a promising alternative to bacteria in water remediation processes. Overall, yeast-based approaches offer promising solutions for the efficient and economical removal of synthetic dyes from industrial wastewater. In conclusion, yeast demonstrates significant potential for the removal of synthetic dyes from wastewater, offering a sustainable and effective solution for addressing the environmental impact of dye contamination in aquatic ecosystems.

## 8. Control of yeast treatment systems

For designing wastewater treatment systems, design parameters, feed characteristics and operational conditions should be fully understood (Fig. 3). Also, it should be noted that seasonal fluctuations (such as changes in temperature, UV radiation, and rainfall intensity) can affect the composition of wastewater [129]. Processes for treating industrial wastewater are categorised as batch and continuous systems. An industrial batch treatment system consists of collecting a volume of wastewater, treating it chemically, physically, and biologically, and discharging it. Whereas in a continuous system, wastewater is continuously added and the treated water is continuously discharged. When converting from batch to continuous treatment, a large amount of biomass is washed out in the effluent causing a loss of biomass. Five isolated yeasts, *C. utilis*, *C. boidinii*, *C. tropicalis*, *Rhodotorula ruba* and *Trichosporon cutaneum*, were studied in a continuous treatment process in an aeration tank. Biomass from the aeration tank was washed away mostly during the treatment. During the sedimentation process, only those cells that sank to the bottom of the column were returned to the aeration tank. The only yeast cell that stayed in the aeration chamber until the end of the experiment was *C. tropicalis*, probably because it sedimented more quickly than the others. Therefore, it should be considered in a continuous treatment system [130].

In another study, ten yeast strains from different sources were used in a sequencing batch reactor for the treatment of wastewater. Yeast selection in oil-containing wastewater was critically dependent on emulsification ability and hydrophobicity. It is possible that cells with high hydrophobicity are more effective in removing hydrophobic pollutants since the pollutants can reach the cell surface easily. The high emulsification ability of cells also allows them to access hydrophobic pollutants. Three yeast strains (*C. lipolytica*, *C. tropicalis* and *C. halophila*) became dominant because of their hydrophobicity and emulsification ability [88].

DO levels play a crucial role in determining the yeast community structure and treatment performance in yeast treatment systems. A DO level of over 2 mg.L<sup>-1</sup> indicates yeast species have a higher degree of determination, poor sedimentation of biomass, and are more effective at removing COD. In contrast, with a DO level of less than 0.5 mg.L<sup>-1</sup>, microbial biomass settlement was effectively restored and the number of yeast species detected was reduced [131,132].

Generally, yeast treatment takes place in an open system, therefore, other microorganisms such as bacteria or mould species can also compete for growth. It is important to design and control the operating conditions such that they favour yeast dominance and biomass sedimentation if the operation mode is continuous. Fig. 3 shows the design parameters, operational conditions, and

feed characterises that need to be considered for designing and operating the wastewater treatment plant. Since the disinfection of such systems is costly, yeast's ability to grow at low pHs can be utilised to disinfect the wastewater [26]. The optimum pH for yeast growth is 3.0–5.0 [29]. It has been shown that the initial concentration of wastewater could influence yeast growth [133], which can have significant consequences for wastewater treatment efficiency. Low pH has been shown to prohibit undesirable bacteria growth and offers satisfactory condition in a continuous system to favour yeast supremacy [134]. Hence, acidic pHs (<6) are usually employed for yeast wastewater system processes to increase yeast growth and reduce bacterial growth in non-sterile environments [29]. Research has also shown that low pH with high COD loading is required for dominance of the yeast community [29].

Even though it is hard for bacteria to challenge yeast at acidic pH, moulds can survive acidic conditions and can compete with yeast. Both yeast and moulds consume O<sub>2</sub> and produce CO<sub>2</sub> and higher CO<sub>2</sub> levels in the system could inhibit their growth. It was found that 10% CO<sub>2</sub> was adequate to prevent mould growth in a competitive condition [134]. As below 20%, CO<sub>2</sub> in the aeration mixture has a negligible effect on yeast growth [135]. Previous studies claim that mould *Geotrichum candidum* was assumed to effectively spread in yeast treatment systems, resulting in inadequate settling and reduced treatment. Later, it was found that these filamentous fungal species found in yeast biomass could be specific yeast species with two distinct cell morphologies [26].

## 9. Lipid produced by yeast grown in wastewater

A wide range of carbon sources can be converted by oleaginous microorganisms into intracellular lipid molecules, resulting in high lipid production. During the stationary phase of microbial growth, these lipids are also called single-cell oils (SCOs) and are synthesised when carbon is abundant and nitrogen is limited. Oleaginous yeasts have a high lipid content, which makes them ideal candidates for producing lipids and oils, which can then be commercially valuable. In recent years, oleaginous yeasts have gained attention due to their easy adaptation to the environment and their ability to produce high cell densities of lipids or oils with either waste, low-cost and abundant raw materials [136]. It is also possible to improve oleaginous yeast's lipid accumulating ability by altering its production process. By adding an excess amount of carbon sources, such as sugar, polysaccharides, or glycerol, the composition of culture media can be altered to create stressful conditions for the yeast. As a result of this, the oleaginous yeast was deprived of nitrogen, which allowed it to accumulate more lipids due to nitrogen starvation [137]. Additionally, other factors also contribute to the accumulation of lipids in a growth medium, such as the carbon-to-nitrogen ratio, dissolved oxygen concentration, reaction temperature, and pH of the growth medium [138]. It should also be noted that every yeast strains has a different lipid accumulation ability; therefore, several strains of oleaginous yeast have been isolated and characterised in the last few decades. Despite the fact that this process is still ongoing, it shows the diversity of organisms that accumulate oil [139]. To evaluate the feasibility of producing biodiesel from high-lipid cell cultures, five oleaginous yeasts were used to produce lipids by using glucose and sucrose as carbon sources. These five strains *Cryptococcus* sp. SM5S05, *Moesziomyces eriocauli* SJ3L01 and SJ4L09, and *Pseudozyma* spp. FN20L03 and SJ4L03 were collected and isolated. Among all the strains tested, *Cryptococcus* sp. SM5S05 accumulated the highest amounts of intracellular lipids. It was also found that the ratio of carbon to nitrogen and the nitrogen concentration strongly determined the accumulation of lipids [140]. Optimisation of lipid determination can be achieved by using a statistical

approach. In addition to saving time, it would also save resources. Therefore, Yadav et al. [141] used response surface methodology (RSM) with a central composite design (CCD) to investigate lipid production using low-cost pre-treated *Brassica juncea*. Following 5 d of incubation at 30°C, pH 6.0, and 32.50 g.L<sup>-1</sup>, maximum biomass of 32.5 g.L<sup>-1</sup> and lipid content of 11.05 g.L<sup>-1</sup> were obtained [141].

In conclusion, oleaginous yeasts have emerged as valuable organisms for lipid production, particularly during the stationary phase of microbial growth, leading to the synthesis of single-cell oils (SCOs). Their high lipid content makes them ideal candidates for producing commercially valuable lipids and oils. Recent research highlights the potential of oleaginous yeasts in lipid production, showcasing their significance in the sustainable production of biodiesel and other lipid-based products [142].

## 10. Conclusions

Yeast exhibits potential for both secondary and tertiary treatment processes. In secondary treatment, such as the conventional activated sludge (CAS) method, yeast faces competition from a combination of flocculated bacteria, fungi, protozoa, and rotifers. For instance, yeast treatment not requires pre-treatment steps for wastewaters that contain oils and greases and not produces high levels of sludge and greenhouse gases (CO<sub>2</sub> and NO<sub>x</sub>), which require disposal, thereby reducing the operational cost.

Yeast wastewater treatment can result in a decrease in oxygen demand to approximately 60% of that required in conventional activated sludge (CAS) systems, as yeast flocs have a porous structure that facilitates oxygen diffusion. Consequently, yeast can consume carbon at a rate of 3–5 times faster than activated sludge. Unlike typical CAS, yeast possesses the advantage of being able to utilise various sources of carbon, nitrogen, and phosphorus for its growth. Moreover, yeast demonstrates high tolerance towards factors such as low pH, high salinity, organics, antibiotics, sterilisers, and others. The optimal pH range for yeast growth is between 3.0 and 5.0. The presence of a low pH inhibits the growth of contaminating bacteria and promotes the dominance of yeast, particularly in non-sterile conditions.

The one downside is that most of the investigation reported here has been executed at a laboratory scale. It is now time for this technology to be scaled up, for industrial use.

## CRedit authorship contribution statement

**Obaidullah Mohiuddin:** Conceptualization, Investigation, Methodology, Resources, Visualization, Writing – original draft. **Adam Harvey:** Project administration, Supervision, Writing – review & editing. **Maria Teresa Orta Ledesma:** Funding acquisition, Writing – review & editing. **Sharon Velasquez-Orta:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

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## Conflict of interest

This review article was written without any influence of any competing financial interests or personal relationships of the authors.

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## Supplementary material

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## Data availability

Data will be made available on request.

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