Co-Culture of Yeast-Microalgae Consortium for Bio-Lubricant and Carotenoid Production and Waste Water Treatment: A Systematic Review

Abstract

The potential of co-culturing yeast and microalgae for bio-lubricant and carotenoid production, as well as wastewater treatment were examined in this systematic review. PICOS framework was used to ensure a thorough approach to the literature review while PRISMA guidelines were followed for a structured approach. Search was conducted in two major databases that are Web of Science and Scopus yielding 134 initial records. 42 duplicate entries were removed followed by rigorous screening process based on relevance to the topic, peer-review status and full texts' availability among others. Finally, 51 papers met all relevant criteria. These chosen studies were then classified into various themes such as Yield Optimization, Chemical Composition Analysis, Process Efficiency, Strain Improvement, Extraction Techniques, Commercial Applications. The outcomes demonstrate that under optimized culture conditions yeast-microalgae co-cultures increases bio-lubricant yield significantly and carotenoid content leading to notable enhancement in pollutant removal efficiency during wastewater treatment. In addition, this review indicates that key determinants for co-culture performance include culture conditions, strain selection as well as process scalability. Moreover, industrial applications of these systems include aspects like advanced bioreactor designs or scalable extraction methods highlighted in this study. A comprehensive understanding of the recent studies within this field is provided by the review which also identifies research gaps necessitating further investigations toward achieving optimal utilization of yeast-microalgae co-cultures for industrial purposes in biotechnology.

Keywords: Yeast-microalgae consortium, Bio-lubricant production, Carotenoid production, waste water treatment

1. Introduction

Since the industrial revolution, contemporary civilization has relied on growing populations, fast urbanization, the depletion of fossil fuels, and persistent problems with water pollution. In recent decades, however, these factors have been gravely challenged by the ensuing energy crises and environmental degradation (Tripathi et al., 2019). In this context, the scientific community has faced problems in recent decades to realign the route of using biomass sources that are environmentally benign and renewable, capable of simultaneously meeting the expanding issues of wastewater disposal and energy security in a straightforward and efficient manner, despite the growing concerns about sustainability (Bisht et al, 2022; Sharma et al, 2021). As of right now, microalgae and yeast are thought to be the most viable and affordable biological substitutes that can also concurrently build up substantial lipid concentrations for the manufacture of biofuel in response to metabolic stress, making them a good substitute and renewable energy source (Arora et al, 2019). Large-scale commercialization hasn't been established yet, despite the fact that it has the potential to play a major role in the creation of a sustainable bio-based economy for the production of biofuel. These reasons include poor biomass productivity, technical and financial viability issues such as inefficient harvesting, energy-intensive photobioreactor installation and operation expenses, high water and nutrient demands, a lack of cheap concentrated carbon dioxide, and extra costs associated with dewatering suspended microalgae (Genin et al, 2014). Abdalla et al. (2024) highlighted the multipurpose potential of co-culture systems in integrated bioprocessing by demonstrating that a fungi–yeast–microalgae consortium could efficiently cleanse livestock wastewater while concurrently creating bioethanol. Suastes-Rivas et al. (2024) also optimized the greater heating value of residual biomass from a microalgae–yeast co-culture, indicating that microalgae can represent a viable source for carotenoid extraction and that such biomass may be customized for the manufacturing of bio-lubricants. Further confirming the feasibility of these consortia as dual-purpose platforms for wastewater treatment and the production of value-added bioproducts, Sibisi et al. (2024) reported that co-culture systems, incorporating microalgae with either yeast or bacteria, achieved high COD removal efficiencies from industrial wastewater. Numerous approaches, including as co-culturing or symbiosis, two-stage culture metabolic/genetic engineering, and others, have been used to overcome these problems. Using the least amount of resources possible, co-culturing has been the subject of extensive research recently. Growing two or more species in the same medium to take advantage of each other's metabolic pathways is known as co-culturing. Nonetheless, there are strict guidelines on the kind, quantity, and quality of organisms used in co-cultures (Goers et al, 2014). Oleaginous microalgae and yeast have the most potentially important co-culture interaction; the microalgae provide oxygen for the yeast to absorb carbon substrates, while the yeast releases carbon dioxide to increase algal photosynthesis (Liu et al., 2018). The interaction between symbiotic organisms and microalgal species led to an increase in both the targeted products and total biomass. Furthermore, wastewater collected from urban, agricultural, and industrial runoff can provide the nutrients and water needed for them. This can be a long-term, low-cost investment that serves the dual purposes of producing biofuel and bioremediating wastewater (Mantzorou & Ververidis, 2019; Bisht et al, 2023).

The physical technique (such as screening and filtration), chemical approach (such as chemical precipitation and adsorption) Azimi et al., 2017), and biological method (biosorption, bioprecipitation) are now the primary ways used to remediate wastewater pollution. These techniques have the benefit of eliminating various materials from wastewater and eliminating contaminants using various techniques. For instance, heavy metals in wastewater may be eliminated using the ion exchange approach, whereas filtration can remove both big and tiny particles. Some drawbacks of these treatment systems include unequal removal efficacy, high installation costs, and unfeasibility, which can lead to secondary contamination and make further treatment more challenging (Dutta et al., 2021).

The baking, brewing, and pharmaceutical sectors all make extensive use of yeast. Yeast can extract biomass efficiently and affordably because it has strong sedimentation and dehydration qualities (Ray et al., 2022). According to a different research, yeast may reduce industrial effluent's COD by 70% in 6.3 hours. It has been established by earlier research that yeast by itself is a very effective wastewater treatment method (Song et al, 2022). Recently, some researchers (Walls et al., 2019) employed a co-culture of microalgae and yeast to treat wastewater. They discovered that the co-culture produced relatively low production of microalgae and yeast, which they believed was caused by pH fluctuations, but it also acquired great nutrient removal efficiency (96 % nitrate, 100 % total ammonia nitrogen (TAN), and 93 % orthophosphate). The benefit of co-culturing yeast and microalgae is that the oxygen the latter create may be taken up by the former as a carbon substrate, allowing it to emit carbon dioxide, which in turn encourages the photosynthesis of the latter. Additionally, there is some effect from the way that yeast and microalgae are cultured (Song et al., 2022).

Yeast and microalgae symbiosis have been thoroughly investigated in a variety of contexts and approaches. It has been shown that the combination of these two microbes improves lipid production, biomass concentration, and growth rate. (Qin et al. 2019) enumerated the advantages of microalgae-yeast binary culture over individual culture; (I) In a binary culture containing both yeast and microalgae, the two species benefit from each other's production of carbon dioxide as a metabolic gas that the heterotrophic yeast produces and the autotrophic microalgae consume; (II) Certain secondary metabolites secreted by the microalgae promote the development of yeast cells; (III) The balance of carbon dioxide and oxygen in binary culture systems has a synergistic impact on adjusting the pH in culture for increased growth; (IV) Nitrogen depletion occurs earlier in binary cultures than in individual cultures, directing metabolic fluxes toward lipid synthesis (Alam et al., 2022). Microalgae are naturally photosynthesis-driven cell factories that run on sunshine. They are also potential candidates for nitrogen removal, phosphorus removal, carbon utilization, and oxygen creation. High oxygen levels and organic exudates from microalgae encourage the growth of heterotrophic aerobic yeast in the culture at the same time. In exchange, yeasts create CO2 through the fermentation of organic compounds, which stimulates the growth of microalgae and the generation of lipids (Magdouli et al., 2016). Prior research has documented a notable rise in biomass and lipid production when utilizing a co-cultivation approach between microalgae and yeast as opposed to a pure microalgae culture. Zhang et al. (2014) concluded that dissolved oxygen (DO), O2-CO2 equilibrium, pH balance, substrate exchange, and other elements in the mixed culture system had a significant impact on the symbiotic relationship and the synergistic effects on the cell development in such a co-culture (Zhang et al., 2014; Ray et al, 2022).

This min objective of the present study is to thoroughly analyze the body of research on the co-cultivation of yeast-microalgae consortia, with an emphasis on the uses of these systems in wastewater treatment, carotenoid and bio-lubricant production. One interesting route for long-term biotechnological applications is the co-cultivation of yeast and microalgae. In addition to exploring how the synergistic interaction between yeast and microalgae might maximize the production of high-value bioproducts including bio-lubricants and carotenoids, this study aims to gather and critically examine the developments in this subject. The study attempts to give a thorough knowledge of the possibilities of these co-culture systems in raising product yields, increasing process efficiencies, and aiding in the development of green technologies by combining research findings. Furthermore, in the context of wastewater treatment, this work attempts to investigate the environmental advantages of yeast-microalgae co-cultures. Through efficient bioremediation procedures, the co-culture technique not only facilitates the bioproduction of valuable chemicals but also provides a long-term solution for reducing environmental pollution. This study aims to determine the critical elements affecting these systems' scalability and efficiency in industrial applications through a methodical literature survey. In the end, it is anticipated that the review's conclusions will guide future investigations and useful applications, advancing environmentally friendly biotechnology and environmental management techniques.

We adhered to these procedures throughout our work in order to achieve our objectives, integrating Web of Science and Scopus—two significant databases—into our thorough review of the literature. Since they include publications from several scientific disciplines, such as engineering and telecommunications, these databases are extensive. The search procedure included an advanced search in which pertinent resources were located using a mix of methodical choices that guaranteed accuracy and comprehensiveness. To find the most current trends in this field, the search was restricted to articles published between 2014 and 2024. Using the terms "microalgae-yeast consortium," "yeast-microalgae co-culture," and other associated expressions as keywords (or search terms), a wide range of research on this topic were found.

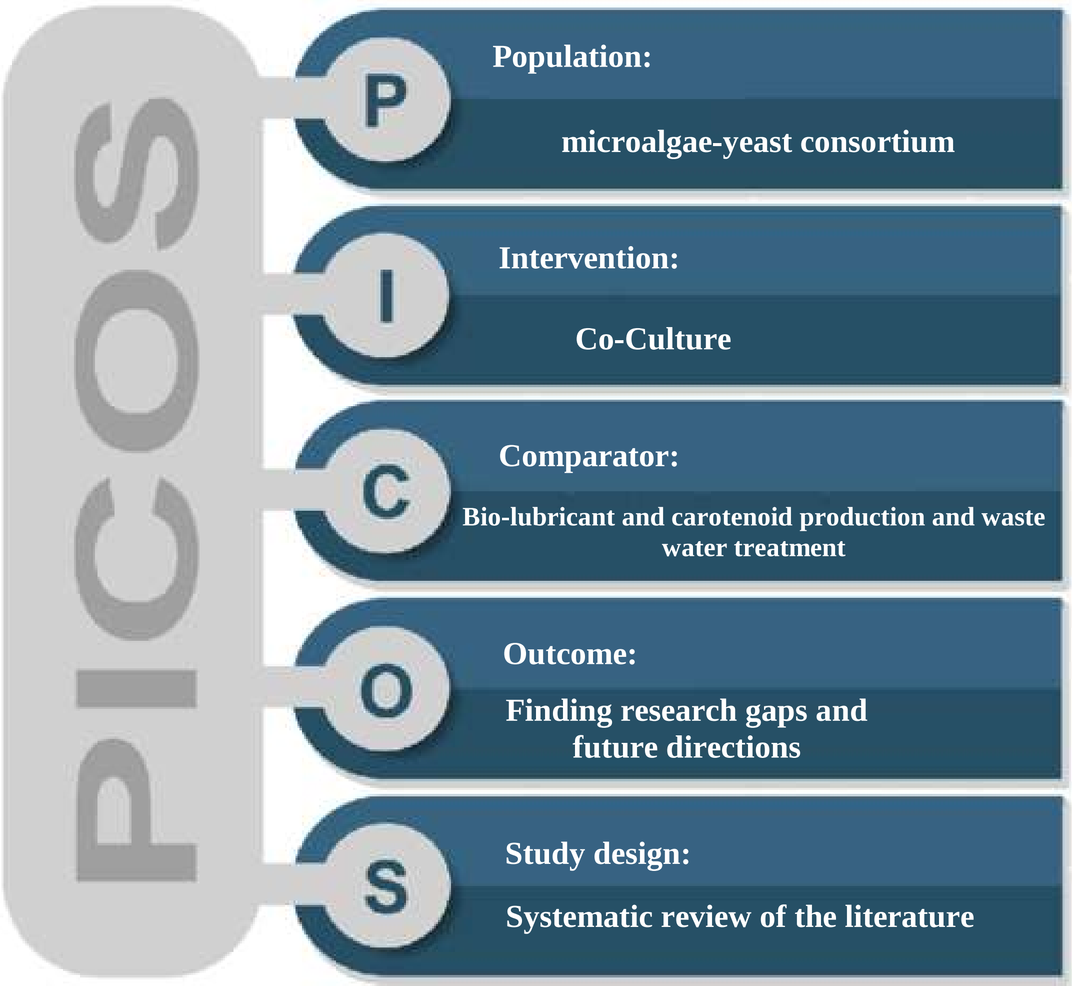

Figure 1. PICOS search terms

In this systematic review, the PICOS (Population, Intervention, Comparison, Outcomes, and Study Design) framework was employed to structure the research methodology and guide the selection and analysis of relevant studies. The "Population" in this context refers to studies focusing on yeast-microalgae consortia utilized in various biotechnological applications. The "Intervention" encompasses the specific co-culture techniques and conditions employed to enhance bio-lubricant and carotenoid production, as well as wastewater treatment efficacy. For the "Comparison" aspect, studies comparing different co-culture methods, single-species cultures, or alternative biotechnological approaches were considered. The "Outcomes" were centered on the efficiency and effectiveness of bio-lubricant and carotenoid production, along with the success of wastewater treatment processes using these consortia. Finally, "Study Design" included all relevant experimental, observational, and case studies that provided quantitative or qualitative data on the performance of yeast-microalgae co-culture systems. By applying the PICOS framework, the review ensured a systematic and comprehensive approach to identifying and evaluating the most pertinent literature in this field.

Using this approach allowed us to identify and assess relevant studies meeting specific inclusion criteria. This made it easier for us to categorize findings from various studies into different types. Data that were necessary such as objectives of investigations conducted, techniques employed by researchers during their work along with the results obtained were extracted by means of an appropriate data extraction form. Through this methodological implementation consistency was ensured within our review hence making it more meaningful based on which we draw some conclusions regarding current state of microalgae-yeast consortium research area.

Research questions

RQ 1: How do different co-culture conditions of microalgae-yeast consortium impact the efficiency of bio-lubricant and carotenoid production?

RQ2: What is the effectiveness of microalgae-yeast consortium in wastewater treatment compared to traditional single-species cultures or other biotechnological methods?

RQ 3: What are the key challenges and limitations in scaling up the yeast-microalgae co-culture systems for industrial applications, particularly in the production of bio-lubricants, carotenoids, and wastewater treatment?

Novelty of the Study

A number of fresh viewpoints on the state of knowledge about yeast-microalgae co-cultures are presented in this systematic study. The main innovation is its thorough assessment of the co-culture systems as integrated platforms for wastewater treatment as well as biotechnological tools for the production of bio-lubricants and carotenoid, which concurrently address sustainability issues in resource recovery and environmental management. This study highlights the synergistic impact of co-cultures on increasing product output while lowering environmental footprints, in contrast to earlier research that mostly concentrated on improving lipid or carotenoid production individually (e.g., Qin et al., 2019; Alam et al., 2022).

New Insights into Process Integration

This review's emphasis on the incorporation of bio-lubricant and carotenoid synthesis into wastewater treatment procedures is one of its main features. Although this dual-functionality approach has received little attention in previous studies, it is essential for creating systems that are both environmentally benign and economically feasible (Mantzorou & Ververidis, 2019). The study demonstrates how co-culture dynamics may be adjusted to produce high-value chemicals and remove pollutants effectively at the same time, especially from industrial effluents that contain organic, nitrogen, and phosphorus impurities.

Advanced Co-Culture Interactions and Metabolic Pathways

Investigating the little-studied metabolic interactions between yeast and microalgae is another interesting aspect. Utilizing the latest developments in metabolic engineering and adaptive evolution (e.g., Alam et al., 2022), this study offers a framework for creating co-cultures that optimize lipid biosynthesis pathways and maximize resource consumption. Additionally, it emphasizes how crucial secondary metabolite exchanges are for enhancing co-culture stability and productivity—a notion that was only briefly discussed in previous studies (Ray et al., 2022; Zhang et al., 2014).

Emerging Trends in Bioreactor Design and Scalability

This paper presents new bioreactor design considerations, with an emphasis on hybrid systems that combine continuous flow systems to minimize operating downtime with photobioreactors for light optimization. With a focus on cost-effective configurations, the scalability of these designs for industrial applications—which is sometimes a barrier in converting lab-scale results into practical solutions—is rigorously investigated (Genin et al., 2014; Magdouli et al., 2016).

Addressing Research Gaps in Yeast-Microalgae Co-Culture Studies

The study concludes by pointing up gaps in the existing body of knowledge about the long-term stability of co-culture systems in practical settings. It emphasizes how sustainable practices may be integrated into wastewater treatment facilities to lower greenhouse gas emissions and resource waste, and it asks for more research into the life-cycle evaluation of co-culture processes (Yin et al., 2018; Velasquez-Orta & Mohiuddin, 2023).

2. Methods

Current study used a systematic literature review (SLR) technique which is an exhaustive approach to the reviewed literature. Steps in SLR include clearly stating the research question or objective that the systematic review seeks to address, performing a comprehensive and systematic scan of all relevant literature sources, screening those studies that meet pre-defined inclusion and exclusion criteria, extracting relevant data from selected studies using an extraction form that has been standardized, and analyzing and synthesizing extracted data from individual studies (Manchikanti et al., 2009; Lichtenstein et al., 2008).

This systematic review was carried out using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework as a guidance. There was the choice of PRISMA to be employed as the guiding protocol for this review because it encourages transparency and comprehensive reporting. Adhering to PRISMA guidelines aimed at guaranteeing clarity and reliability of our review process through transparent reporting methods, results and conclusions. The utilization of PRISMA offers an organized approach to collect, analyze and synthesize pertinent information on a given topic to ensure that it is not a mere summary but rather a systematic examination. This method makes the review more rigorous and reproducible, hence lending credibility and trustworthiness to its findings in turn (Liberati et al, 2009). It has several check-lists which can help the writer and reviewer create useful review papers.

To prevent replication of outcomes while keeping the integrity of the study intact we had recommended certain precautionary measures like removing duplicated articles with multiple searches. However, some journals may appear in different databases; hence we scrutinized search results from Web of Science versus Scopus thus eliminating any repetitively presented literature sources. By doing so, we were able to make our review process simpler by ensuring that no paper is included twice except for one copy only hence making sure that duplication is avoided thereby increasing credibility of our results. In choosing keywords for our systematic research, we took an extremely elaborate approach so as to have a comprehensive yet relevant search strategy. Initially there was an extensive examination of existing literature including key terms used in similar studies published with respect to our area of interest. These initial keywords were then refined and expanded upon further with some being further added or omitted altogether depending on their relevance in relation to the study topic under discussion. Figures 2-5 provide an analytical summary of the number of articles in the Web of Science database by different search terms associated with the microalgae-yeast consortium. These figures reveal research trends in different fields that highlight where interest has been growing and concentrating within this field during recent times. Basically, they demonstrate shifts in scholarly attention over years as well as amounts of investigation into different aspects of self-driving car requirements. In WOS, there are 62 documents (39 articles).

Figure 2. WOS 62 Articles by Category ("Yeast-microalgae co-culture" OR "microalgae-yeast consortium" OR "yeast-microalgae" OR “yeast and microalgae consortium” OR “co-culture of Yeast-microalgae”)

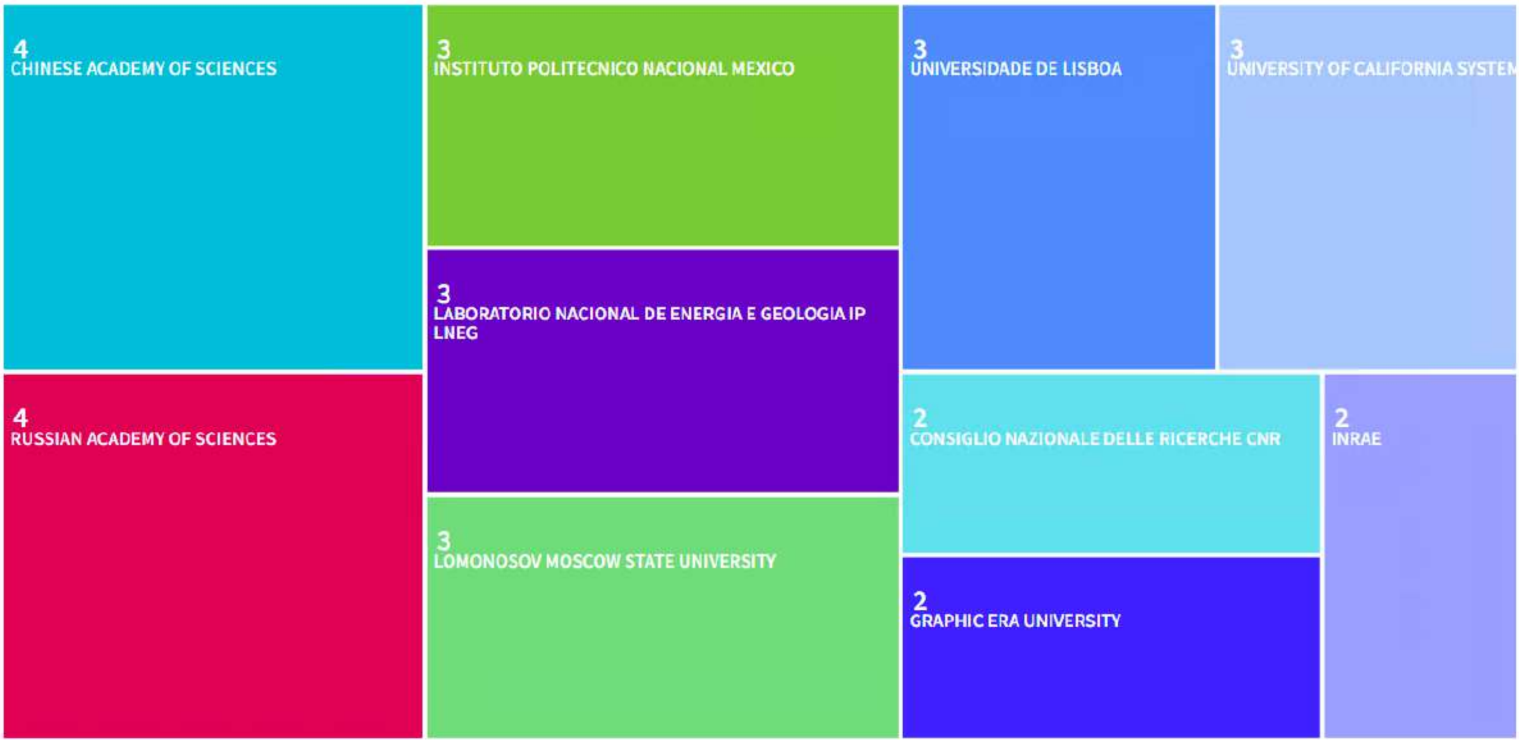

Figure 3: WOS documents by affiliation

Figure 4. WOS documents by Country/Regions

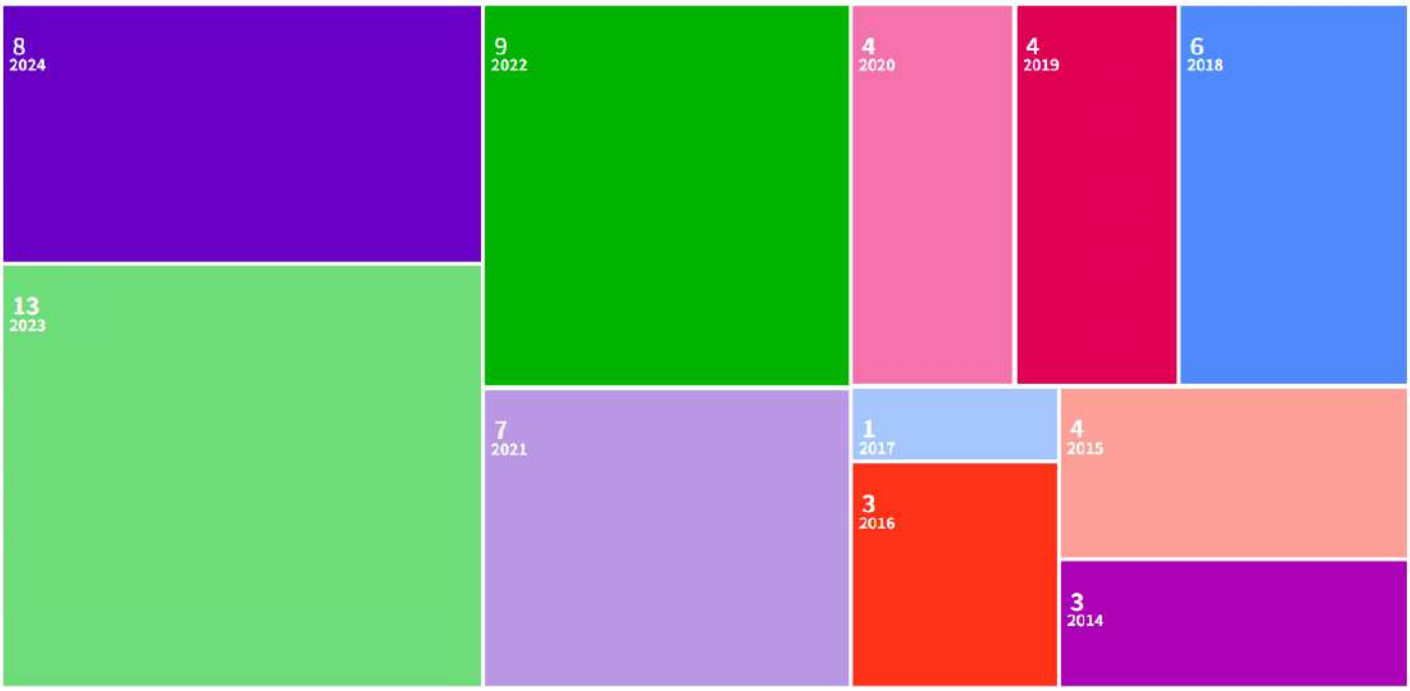

Figure 5. WOS documents by Publication Year

We searched all the databases using Advanced Search Option that enabled us narrow our search down especially on research topics. We thus conducted a search tailored for the years 2014–2024. Thereafter, we used BOOLEAN operators to meet research objectives.

With this set of research phrases in conjunction with BOOLEAN operators specifically searching within the ABSTRACT-TITLE-KEYWORDS field only a few publications were obtained. As indicated in Figure 10, this search found 62 outputs in WOS (39 articles) and 72 documents in Scopus (42 articles). Given the multitude of journals available across different databases, there was a high probability of duplication.

Out of 134 items, we excluded 46 as they were duplicates. After merging all database findings and eliminating duplicates an initial screening process was done. The first screening stage was based on title only. A coding scheme was designed to make careful decisions about which articles to accept or reject at the first screening stage. By employing this same coding method, abstracts were screened and review papers were excluded while non-related ones were eliminated alongside those in other categories and fields.

Scopus database was explored in Figures 6 to 9 which carried out a comprehensive assessment of publications with the help of varied search terms, affiliations as well as countries. These charts provide an extensive view of research output showing contributions from different parts of the world and academic institutions. The study identifies leading nations and establishments in (co-culture of yeast-microalgae consortium for bio-lubricant and carotenoid production and waste water treatment) research thus pointing out major players in this field. Moreover, this globalizes efforts made towards studying yeast-microalgae consortium by underscoring international collaboration among other things. Looking at them enables us also know where most studies have been done and what drives academic discussion around such important matters.

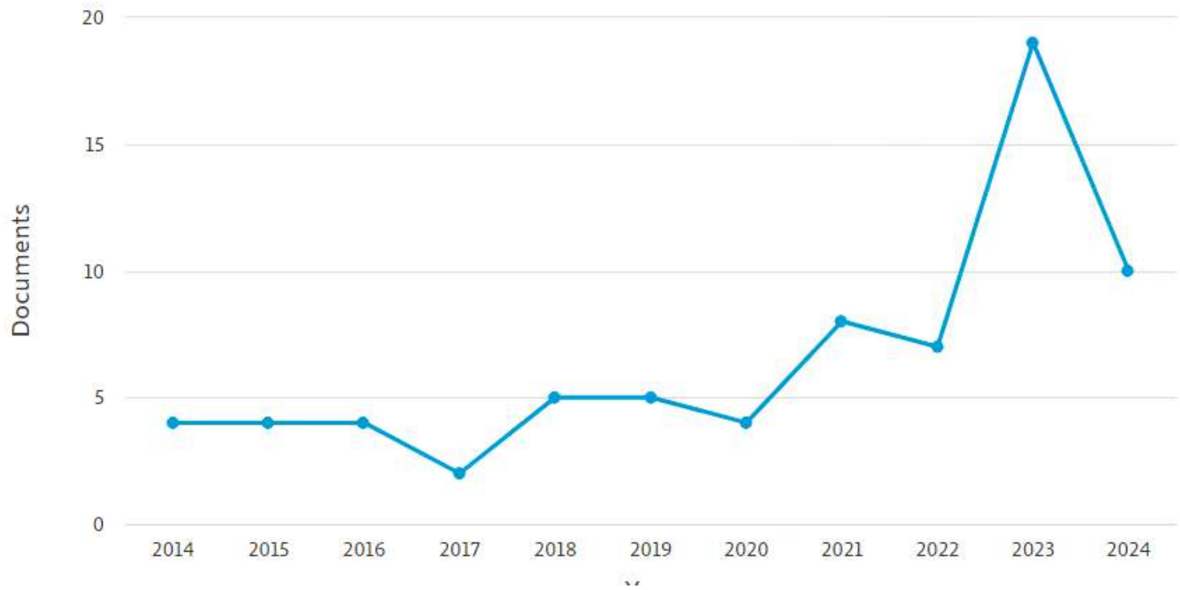

Figure 6: Scopus documents by year of publication (72 Papers)

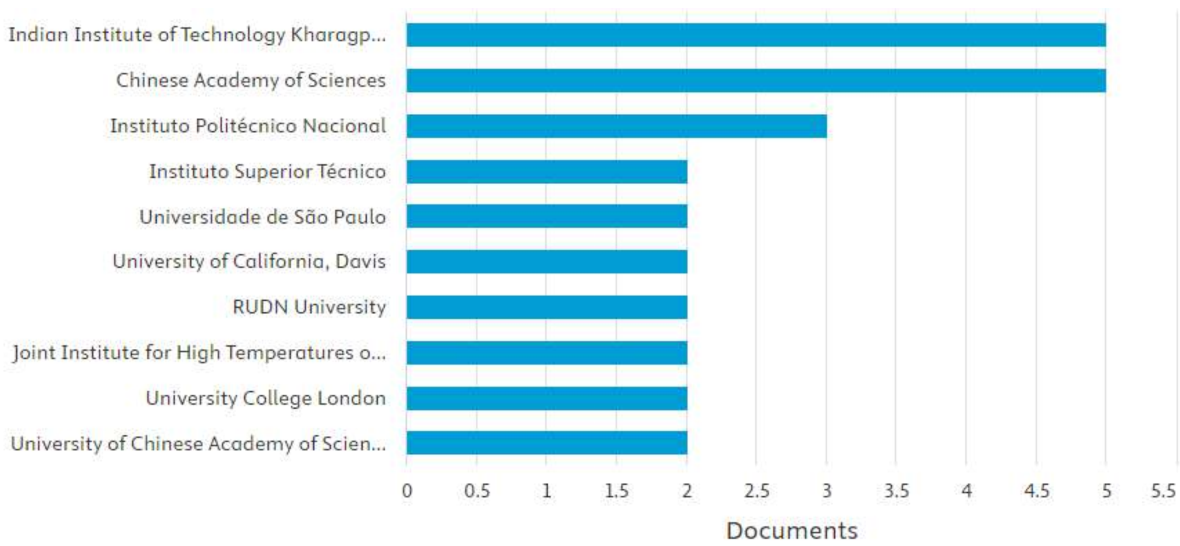

Figure 7: Scopus documents by affiliation

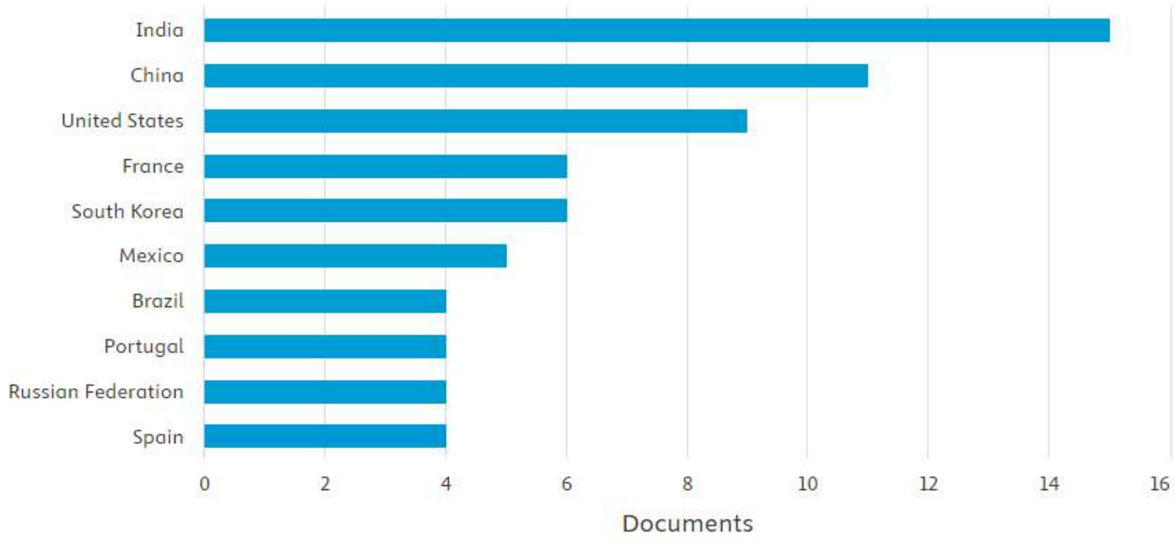

Figure 8: Scopus documents by Country/Territory

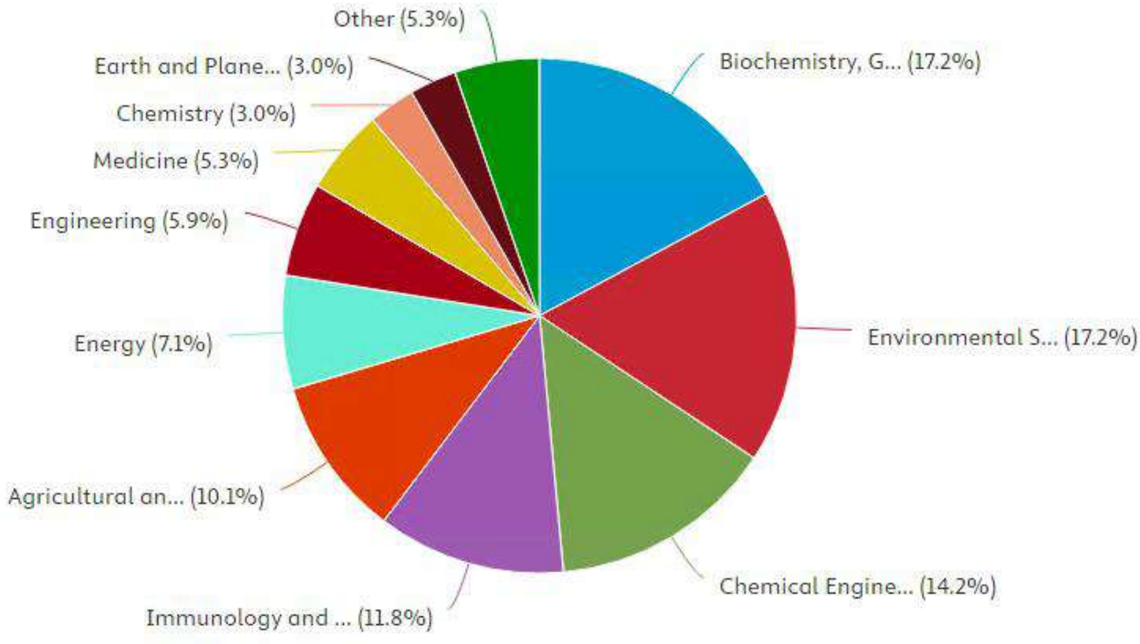

Figure 9: Scopus documents by category of study

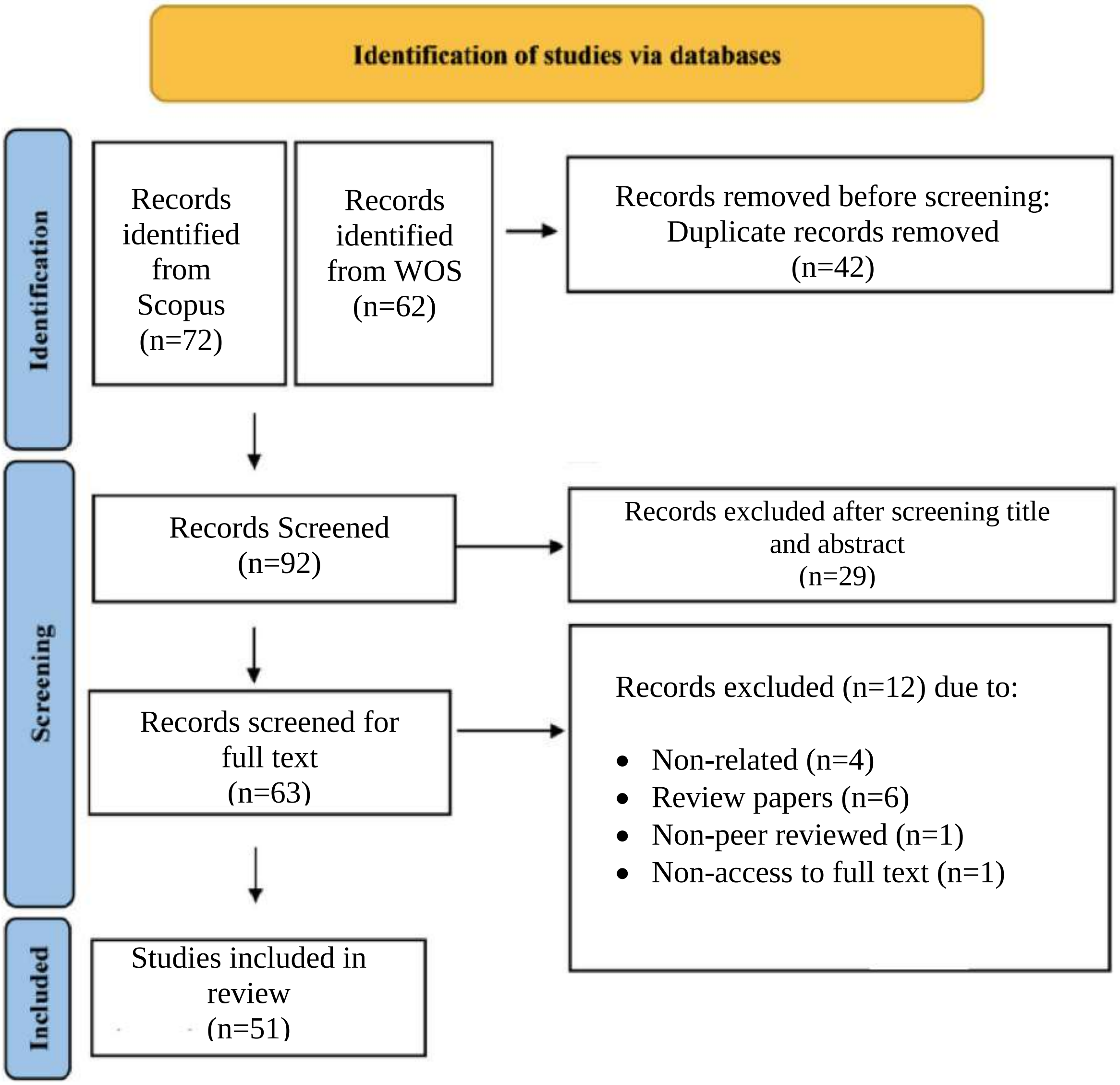

Figure 10. PRISMA Flow Diagram

2.1. Exclusion Criteria

It was necessary to set clear exclusion criteria in order to have relevant and good quality studies. This first criterion involved non-related fields of study. Therefore, a wide range of articles were found especially on general microbiology, chemical engineering, environmental science and other multidisciplinary subjects. Nonetheless, research papers that did not focus on either the co-culture of yeast and microalgae or bio-lubricants, carotenoids or wastewater treatment were disqualified from this review. The step was important as it helped keep sight of the main objective.

The second group excluded review papers from their systematic review. Review articles could be an essential source for a broader perspective on research trends but lacked original data and novel experimental findings which are essentials for a systematic review meant to evaluate whether certain methodologies or processes are effective and efficient in practice. Mainly, empirical studies that provided detailed results and discussions about co-cultivation of yeast with microalgae generated these conclusions which were based on direct evidence rather than being synthesized summaries of existing literature.

Another significant exclusion criterion involved eliminating non-peer-reviewed papers; only peer-reviewed articles were included in this analysis as a measure of ensuring scientific credibility. Non-peer reviewed publications like preprints conference abstracts and unpublished thesis materials were left out because they may not have undergone rigorous expert assessment within the field concerned thereby undermining their trustworthiness where scientific scrutiny is concerned. Quality control was ensured by excluding any work that has not been carefully scrutinized through peer review in order to maintain the integrity of this review.

Lastly, the whole studies whose full texts could not be accessed were removed from this review exercise. Despite comprehensive search through various academic databases some articles could not be retrieved fully. This limitation could likely introduce some bias if those studies had relevant data presented. Nevertheless, these articles had to be discarded so as to ensure that there was completeness in analysis hence making it possible for more accurate and comprehensive evaluations to be conducted. The exclusion process of these studies was well documented so that the selection procedure would remain transparent and the overall methodology of the review would maintain its rigor.

3. Results

This study groups papers into several themes to know the applications of yeast-microalgae consortium for bio-lubricant and carotenoid production and waste water treatment.

Table 1. Coding for data extraction

Category	Main themes	Codes
Bio-lubricant	Yield Optimization	1. Influence of culture conditions (e.g., temperature, pH, nutrient availability) 2. Effect of yeast and microalgae strain selection on yield 3. Process scalability and industrial application
	Chemical Composition Analysis	1. Fatty acid profile characterization 2. Evaluation of bio-lubricant properties (e.g., viscosity, thermal stability)
	Process Efficiency	1. Energy consumption in bio-lubricant production 2. Cost-effectiveness of co-culture systems 3. Comparison with conventional lubricant production methods

Carotenoid Production	Strain Improvement	1. Genetic modification and metabolic engineering for enhanced carotenoid production 2. Screening of high-carotenoid producing strains
	Extraction Techniques	1. Solvent-based extraction methods 2. Green extraction techniques (e.g., supercritical fluid extraction) 3. Optimization of extraction yield and purity
	Commercial Applications	1. Use of carotenoids in food and pharmaceutical industries 2. Stability and shelf-life of carotenoid products 3. Market potential and economic analysis
Wastewater Treatment	Pollutant Removal Efficiency	1. Reduction of organic load (e.g., BOD, COD) 2. Nutrient removal (e.g., nitrogen, phosphorus) 3. Heavy metal sequestration
	Bioreactor Design	1. Types of reactors used (e.g., photobioreactors, membrane bioreactors) 2. Reactor configurations for optimized treatment 3. Scale-up challenges and solutions
	Environmental Impact	1. Assessment of ecological benefits 2. Life cycle analysis of co-culture-based wastewater treatment 3. Reduction of treatment costs and resource recovery
Co-Culture Dynamics	Interaction Mechanisms	1. Symbiotic and synergistic relationships between yeast and microalgae 2. Impact of co-culture ratio on productivity 3. Competition for resources and its mitigation
	Growth Kinetics	1. Monitoring of growth rates in co-culture systems 2. Modeling and prediction of growth patterns 3. Influence of environmental factors on co-culture stability
	Biomass Composition	1. Evaluation of lipid, protein, and carbohydrate content 2. Influence of culture conditions on biomass yield 3. Post-harvest processing of biomass

Bio-lubricant production

Bio-lubricant production in a yeast-microalgae co-culture system requires the optimization of yield. The lipid composition and content in microalgae determine the overall amount of bio-lubricants that are extracted. There are some factors that contribute to this, including the choice of substrate, which will depend on the ratio of yeast to microalgae, culture conditions such as temperature, pH and nutrient availability among others. For example, nitrogen limitation lead to storage of excess carbon by lipids in high carbon-to-nitrogen (C/N) ratios in microalgae. Additionally, timings for harvesting should be chosen wisely—this would ensure maximum lipid yield if done at peak lipid accumulation time. In order to maximize bio-lubricant yields under certain constraints, researchers often use statistical tools like response surface methodology (RSM), which systematically optimizes these variables.

A co-culture system may lead to various lipids with different fatty acid profiles. These profiles are responsible for determining such characteristics of a biolubricant as viscosity, thermal stability and biodegradability. Therefore, gas chromatography-mass spectrometry (GC-MS) is commonly used to identify and quantify the fatty acids present within a bio-lubricant sample. The typical fatty acids produced by yeast include palmitic acid, oleic acid as well as linoleic acid which provide different contributions to the final performance of the product. For instance, presence of unsaturated form can increase flow ability at low temperatures thus making it suitable for specific industrial purposes. By analyzing chemicals mixture involved researchers can create their own co-cultures where they can produce desired properties that will make them competitive against conventional petroleum-based lubricants (Samavi & Rakshit, 2022; Malik et al, 2023; Masri et al, 2018). Bioreactor process efficiency is important to the whole economics of bio-lubricant production with yeast-microalgae consortium. Efficient processes reduce waste, save energy and increase raw material utilization, which are imperative in scaling up manufacturing capacity. For example, one way to improve process efficiency is by integrating continuous culture methods that ensure bio-lubricants can be continuously harvested. This method contrasts with batch cultivation where the culture is grown, harvested and restarted leading to downtimes and low overall efficiencies commonly experienced. Furthermore, bioreactor design improvements like photobioreactors enhancing light distribution and CO2 usage contribute to better process economy. The efficiency of the whole process can also be improved by coupling bio-lubricant production with carotenoid extraction or wastewater treatment among other bioprocesses. Genetic and metabolic engineering of yeast and microalgal strains used in co-culturing often forms part of yield optimization strategies for bio-lubricant production. Researchers usually alter specific metabolic routes to enhance lipid biosynthesis resulting in high yields of the lubricants as such fats are produced. Additionally, overexpressing enzymes involved in fatty acid synthesis pathway may lead to higher lipid accumulation. Besides genetic modification, adaptive laboratory evolution (ALE) enables selection of strains that have developed tolerance to high stress conditions such as high salinity or nutrient limitation that are common at large scale cultivation stage. Such stains can operate at high productivity even under adverse environments thereby increasing industrial-level yields for biolubricants (Hossain et al, 2019; Shahbaz et al, 2022; Rai & Gurung, 2022; Aboelazayem & Alayoubi, 2021; Farfan-Cabrera et al, 2022).

The achievement of yield improvement and changes in the chemical composition during biolubricant manufacturing process has far reaching implications for industrial activities. Environmentally friendly processes that give rise to bio-lubricants with most desirable chemicals can lead to making new types of sustainable lubricants to be used in diverse areas including automotive, machinery, and manufacturing. The ability to modify fatty acid profile according to strain selection and culture condition optimization is important for producing bio-lubricants intended for particular uses like high-temperature environments or food-grade applications. Additionally, attainable process efficiency using improved cultivation techniques and bioreactor designs ensures that production costs of bio-lubricants are low enough enabling their adoption on an industrial scale.

Carotenoid Production

Strain improvement plays a key role in improving the production of carotenoids in yeast-microalgae co-culturing. Carotenoid production can be different depending on the type of strain for both yeasts and microalgae. Among the techniques used to improve strains with high carotenoid content are genetic engineering and adaptive laboratory evolution (ALE). Genetic engineering technique introduces new genes or overexpresses existing ones that are connected to biosynthesis pathways of carotenoids such as phytoene synthase or lycopene cyclase. These changes enable more significant flow through the path of carotenoid synthesis leading to increased carotenoid accumulations. Adaptive laboratory evolution on the other hand is based on the selective pressures which include exposing organisms under investigation to conditions such as high light intensity, oxidative stress so as to obtain nature selected strains that will have an improved capacity for producing higher levels of carotenoids. In combination, these tactics can generate powerful yeast-microalgae consortia that yield commercially viable levels of carotenoids. The process of extracting carotenoids from yeast-microalgae co-culture affects yield and purity directly (Stephens et al, 2015). These methods typically employ organic solvents like acetone, ethanol or hexane for dissolving out keratinoid from biomass like through solvent extraction mechanisms (traditional method). However, incomplete extraction among other challenges, is often encountered during this procedure; another major issue being about toxicity posed by use of solvents in this procedure. Modern methods such as supercritical fluid extraction (SFE) and ultrasonic-assisted extraction (UAE) have been proposed to overcome these limitations. Super critical fluid extraction which employs super critical Co2 as a solvent stands out because it only extracts desirable foods without leaving toxic residues hence making this approach environment-friendly and apt for food and medical applications. Ultrasonic assisted extraction exploits ultrasonic waves that cause breakdowns in cell walls by increasing solvent permeation thereby boosting extraction efficiency and reducing time required. By applying these modern techniques in the process of extraction, one is able to extract carotenoids from co-cultures with high purity and maintained bioactivity which are extremely important for commercial purposes of these substances (Arora et al, 2020; Bharadwaj et al, 2020; LaPanse et al, 2021; Jiru & Abate, 2014; Wass et al, 2021).

Carotenoids produced by yeast-microalgae co-cultures find a wide range of applications in the food, pharmaceutical, and cosmetic industries. The food industry uses carotenoids as colorants and antioxidants that make them suitable for use in beverages, dairy products and baking ingredients. Growing consumer demand for natural and health promoting ingredients has fueled the market for carotenoids especially those sourced from yeast-microalgae consortia which are resilient as well as non-GMO. Carotenoids are also employed in the pharmaceutical sector where they have been associated with several potential health benefits such as lower risk of chronic diseases like cancer and cardiovascular disease. Taking care of oxidative stress through creation of supplements targeted at raising immune function is one other use based on their antioxidant properties. In addition to their anti-aging effects and photoprotective capabilities, these compounds can be used in formulating skincare products that prevent UV induced skin damage resulting from aging. Since there is a great need for carotenes across various sectors, this implies that huge financial rewards could be realized if their production was optimized through yeast-microalgae co-culture systems.

Commercially, carotenoid production can only be viable if the co-culture process is optimized in terms of both yield and cost effectiveness. In this regard, strain improvement and advanced extraction techniques are not enough but optimizing the growth conditions of the co-culture. These conditions include light intensity and temperature, nutrient availability and pH that must be carefully controlled to optimize carotenoid production. Continuous culture systems such as photobioreactors are often employed to maintain the culture in an optimal state for prolonged periods so that there is continuous carotenoids production. Moreover, integrating biotechnological processes such as bio-lubricant production or wastewater treatment with carotenoid production can improve overall process performance while at the same time reducing costs thus making the whole system more sustainable and economically attractive. Thus, through focusing on process optimization, researchers can scale up laboratory-based carotenoids' production to industrial level in order to meet ever increasing demand of these high value compounds (Kumar et al, 2020; Sproles et al, 2021; Wang et al, 2019; Schurr & Kuehnle, 2014; Choudhary et al, 2022).

Wastewater Treatment

Wastewater treatment by co-culturing yeast and microalgae stands as a promising technique due to its high pollutant removal efficiency. Micro algae are great at removing nutrients such as nitrogen and phosphorous from waste water which greatly helps in reducing the levels of these contaminants. On the other hand, yeasts metabolize organic pollutants like complex carbohydrates and proteins that might be resistant for microalgae alone to break down. The synergistic interaction between the two organisms enhances total pollutant removal in co-culture process over other individual organism conventional methods. Such studies have indicated that co-cultures can realize higher nutrient removal rates and biochemical demand (BOD) when assessing the quality of treated wastewater. This high level of efficacy assists not only in meeting environmental regulations but also produces cleaner water for agriculture or industry. The effectiveness of wastewater treatment depends on how bioreactors designed to accommodate yeast-microalgae combination work. The type whether it is open ponds, photobioreactors, or hybrid systems affects growth conditions, interactions among organisms, and overall pollutant removal efficiency. For example, photobioreactors provide well controlled environments with optimal light exposure required for photosynthesis by microalgae such as chlorella species. These systems can optimize access to light and nutrients within the co-culture hence higher treatment efficiency. Advanced designs including continuous operation of co-culture further enhance performance and reliability. The addition of mechanical mixing and aeration systems into the bioreactor prevents settling as well as ensures uniform distribution of both light energy and essential nutrients throughout culture. Costs associated with scalability and maintainability should also be considered, as this technology needs to be used in industrial applications. These cutting-edge innovations would boost process efficiency and help them perform better.

Another important factor that should be considered is the environmental impact resulting from using a yeast/microalgae consortium for wastewater treatment. This approach involves the use of natural organisms to break down pollutants without having to rely on harsh chemicals or much energy. Carbon sequestration is also facilitated by the use of microalgae which absorb CO2 during photosynthesis thereby mitigating greenhouse gas emissions. The biomass produced during the treatment process, which contains rich proteins and lipids, can be harvested for various purposes like biofuel production or as feedstock in biolubricants and carotenoids. This not only minimizes waste but also adds value to the process of water treatment. Nevertheless, the environmental benefits have to be weighed against issues such as disposal of residual biomass and energy consumption needed to maintain proper conditions inside a bioreactor. Life cycle assessments (LCAs) are ideal tools for determining overall ecological footprints with room for further improvement in some areas (Udaiyappan et al, 2017; Le et al, 2019; Kumar et al, 2023; Velasquez-Orta & Mohiuddin, 2023; Yin et al, 2018; Morais et al, 2021). Cheng et al. (2024) demonstrate that an aggregation-algae consortium isolated from a municipal wastewater treatment plant can effectively degrade the antibiotic SMX and remove nutrients, thereby contributing to the Wastewater Treatment theme. Zúñiga-Burgos et al. (2024) investigate polyphosphate synthesis dynamics in Chlamydomonas reinhardtii during phosphate deprivation and resupply, providing valuable design parameters for algal-based nutrient recovery systems from wastewater.

Another important factor is whether or not it will be possible to implement yeast-microalgae co-cultures for treating waste water on a greater scale on an economically viable basis. It is apparent that the treatment costs, reactor building costs plus maintenance expenses are often too much for bioreactor users. To improve the economic potential of this technology, there is need to develop low-cost bioreactor designs that can save energy by controlling culture conditions and utilizing cheap or waste-based feedstocks. On top of these considerations, there is an opportunity to generate some valuable byproducts like bio-lubricants and carotenoids that could partially pay for the treatment cost with other income streams also emerging. The scalability concerns are also important since what works well at lab scale may fail in big industrial systems. Thus, addressing such issues through pilot studies and process optimization are essential for successful commercialization and wide-spread adoption of this technology in wastewater treatment (Al-Jabri et al, 2020; Gondi et al, 2022; Maurya et al, 2022).

Sustainable wastewater treatment technologies can benefit from yeast-microalgae co-culture in future. However, there still exist several challenges that should be addressed before all benefits of this approach can be realized. One main challenge is maintaining stability and balance in the co-culture over long durations especially when faced with variations in environmental conditions as well as differences in waste water compositions. Furthermore, further research should focus on optimizing growth conditions as well as bioreactor designs so that they maximize pollutant removal efficiency while minimizing energy inputs and operational costs. The widespread implementation of this technology will require robust, cost-effective and scalable systems working under real-world settings. But despite these challenges; high pollution removal efficiency; environmental friendliness; potential revenue generation from the products produced together with other factors make yeast-microalgae cocultures a very promising method for managing sustainable wastewater solutions where demand seems to be ever increasing. Moreover, Abdalla et al. (2024) develop a fungi-yeast-microalgae consortium for integrated bioethanol production and effective livestock wastewater treatment, thus aligning strongly with the Wastewater Treatment theme.

Co-Culture Dynamics

In a co-culture involving microalgae and yeast, understanding the interaction mechanisms between these two species is key to overall consortium dynamics and efficiency. As is characteristic with such interactions, the relationship of these two organisms is normally symbiotic as each gain from the metabolic activities of the other. By going through fermentation processes in which carbon dioxide is released, yeast offers an essential microalgal substrate for photosynthesis. Oxygen generated by microalgae forms when light energy splits water during photosynthesis enabling aerobic respiration in yeasts. Additionally, yeast can degrade complex organic substrates into more assimilable forms that can be consumed by algae. This mutualistic relationship increases overall productivity within cocultures because each member sustains growth and meeting metabolism needs of its partner. Understanding these interaction mechanisms is crucial for optimizing the co-culture conditions to maximize biomass yield and product formation (Suastes-Rivas et al, 2020; Yen et al, 2015).

The growth kinetics of the yeast-microalgae consortium also impact dynamics directly since it influences efficiency and productivity hence affecting system performance: The several factors influence individual organism growth rate including nutrient availability, light intensity, temperature and pH within this co-culture structure. Normally, under suboptimal lighting conditions particularly, microalgae grows at a slower pace than yeast does Nonetheless, yeasts alters growth environment in ways that can enhance algal growth For example, maintaining a stable pH concentration with releasing nitrogen derived from essential nutrients Thus oxygen as supplied by small algae determines how much yeast will grow On the other hand if one overpowers another it would disrupt co-culture dynamics and therefore reduce overall system efficacy Therefore there must be a fine interplay between production rates of both bacterial species to maintain high efficacy of the overall process (Luo et al, 2021; Padri et al, 2021; Liu et al, 2018). Sobolewska et al. (2024) explore the growth of yeast in liquid digestate for nutrient and pollutant removal, highlighting the potential of yeast-microalgae co-cultures to improve wastewater treatment efficiency, thus aligning with both Wastewater Treatment and Co-Culture Dynamics themes. Suastes-Rivas et al. (2024) statistically optimize the higher heating value of residual biomass from a microalgae-yeast co-culture, offering insights into co-culture dynamics that may inform future strategies for bio-lubricant production. Ogawa et al. (2024) review the use of filamentous fungal biomass as a platform for immobilizing various cell types, including yeast and microalgae, emphasizing inter-kingdom interactions that are central to Co-Culture Dynamics.

The quality and yield of products like bio-lubricants or carotenoids depend on biomass composition characteristics exhibited in a mixed culture between yeast cells and microalgae cells. The make-up of the biomass is influenced by the above interaction mechanisms, growth kinetics within the consortium and specific culturing conditions. It has been established that microalgae have high lipid profiles for bio-lubricant production, which is why they are also rich in carotenoids. In contrast to this yeast contains proteins and carbohydrates that improve nutritional value as well as enhance functionality of biomass. The co-culture can lead to a synergistic enhancement of these components where the resulting biomass contain more valuable compounds than achievable by any organism alone. To customize its composition for particular aims such as optimization of nutrient ratios and light intensity, a balance between lipids, protein and carbohydrate contents in the biomass may be adjusted at levels making it possible to tailor the growth parameters accordingly. Optimizing the culture conditions and balancing the interaction of the two species are necessary in order to maximize biomass yield in yeast-microalgae co-culture system. For example, factors such as nutrient concentration, initial inoculation ratio, temperature changes and pH influence total biomass yield at large. A right balance ensures that neither the micro algae nor yeast will outcompete one another thus allowing maximum utilization of available resources; this can be achieved if there is an optimal inoculation ratio between microalgae and yeast. Furthermore, supplementations of nutrients may need to be done differently since yeasts and micro algae have different nutritional demands at various phases of growth. These parameters can be fine-tuned to achieve a high biomass yield with its lipid composition as well as proteins or other useful components. Continuous monitoring and adjustments must therefore be made in order to sustain co-culture dynamics while averting imbalances that could reduce productivity (Karim et al, 2021; Szotkowski et al, 2021). Sibisi et al. (2024) assess the efficiency of microalgae-based consortia (with bacteria and yeast) for COD removal in sugar industry wastewater, illustrating how co-culture systems enhance wastewater remediation and reflecting aspects of both Wastewater Treatment and Co-Culture Dynamics.

However, despite having much potential in producing valuable biomaterials through use of yeast-microalgae mixed cultures, several challenges need to be overcome so that they can fully exploit their capabilities. For instance, changes in environmental condition leading to imbalances of growth dynamics makes it hard for them to stay together for long time periods. Additionally, it becomes difficult on how one manages two organisms whereby each requires distinct metabolic needs during optimization process which is a complex task; managing two separate organisms with different metabolic requirements complicates optimization strategies further. Case studies suggest that these challenges could overcome by adopting advanced bioreactor designs and real-time monitoring systems through improvement of bioprocess engineering. In addition, research might usefully test genetically modified strains of both yeast and algal strains with hope improving compatibility and productivity within co-cultures systems. Despite all these problems however this approach has some merits such as possible efficient production bio lubricants / carotenoids or sustainable wastewater treatment making it a very attractive area for further investigations.

Discussion and Conclusions

According to Castledine et al. (2020), the quick adaptation of species important to biotechnology for certain settings and biotechnological processes may be facilitated by the development of microorganisms in the lab, such as yeast and microalgae. Using abiotic elements as selection pressures, the method has primarily been used to single species in pure cultures. A dearth of studies has utilized biotic selection forces, or the existence of other species, to investigate adaptations in an ecological context, and no extensive strain phenotyping in multispecies settings has been conducted (Naidoo et al. 2019; Venkataram et al. 2023). As such, genomic databases almost lack functional gene annotations that are critical to ecosystems. Moreover, little is known about the underlying mechanisms of these interactions over time, perhaps because it is difficult to sustain long-term physical contact across species without one species outcompeting the other.

Researchers suggest that we can get around this constraint by employing ecosystem engineering to create symbiotic states such as obligate mutualisms. Lichens may therefore be considered as an evolutionary precursor of such relationships, although it is not clear if yeast and microalgae normally form symbiotic associations. However, co-cultures involving these microorganisms have immense potential for ecology because they help us understand how interspecies cooperation arises (Oosthuizen et al, 2020). As demonstrated in artificial environments, synthetic yeast-microalgae symbiosis interactions involved complex interplays among the organisms (Venkataram et al, 2023).

Starmer and Lachance (2011) noted that within a microalgal culture system, the latter provide both food-rich habitats and physical protection to yeast while yeast supplies them with fitness-enhancing metabolites like vitamins or organic compounds that assist growth or survival of microalgae. They explored several dynamics in a system where Yeast is grown along with

Micro-algae focusing on possible application in biotech sector particularly bio-lubricant production which could be achieved through wastewater treatment. The article provides a summary of major themes identified in co-culture literature based on our review of relevant publications within this framework thus suggesting directions for future research. In essence, our results highlight the importance of combining different aspects found in literature so far with respect to co-culture frameworks under one systematic analysis which shows various issues pointing to future areas for further studies. Thus, we provide an overview of how industrial biotechnology can utilize co-cultures including their relevance towards sustainable production as well as environmental management. We were particularly interested in understanding the potential for bio-lubricants from yeast-microalgae co-cultures. Our examination revealed that there are species specific metabolic interactions between these two species of relevance for bio-lubricant production. The lipid content is maximized by optimizing culture conditions such as temperature, pH and nutrient availability, which are essential precursors in bio-lubricants. On the other hand, according to our results, the choice of yeast and microalgal strains can enhance or diminish the overall efficiency of lipid accumulation. In terms of vast-scale bioreactors it becomes difficult to balance between growth and product output making industrial application highly unfeasible. Nevertheless, there is a need to select appropriate growth mediums so that there are no limitations on biomass yield.

As another key industry that uses high value products like carotenoids; yeast-microalgae co-cultures have shown great potential. We observed from our review that genetic engineering and selective breeding for improved strain would significantly increase carotenoid yields. The other challenge concerns how best to extract these compounds more profitably from such biomass. Carotenoids have commercial applications in food industries, cosmetics, and pharmaceuticals especially due to their antioxidant qualities. However current methods of extraction are costly and eco-unfriendly. In order to address these issues green chemistry and sustainable extraction technology needs to be enhanced. Future studies can also look into the effects of combined cultures on carotenoid biosynthesis that may open up new avenues towards increased production levels through alternative pathways.

Yeast-microalgae co-cultures have great potential in treating wastewater and this could be one of the most effective ways to manage our environment sustainably. Amongst the many pollutants that these two types of cultures are very good at taking off include nitrogenous and phosphorous nutrients, heavy metals as well as organic contaminants. This is because such co-culture systems play a vital role in determining the efficiency and scalability of treatment processes. The advantages of these co-cultures in wastewater treatment are huge; some of them include reduction of eutrophication in water bodies, making it possible to recover important resources from waste streams. However, integrating these systems into existing urban waste water infrastructures has remained a challenge for many developers. In addition, future studies should therefore focus on developing a long-term stability, operational efficiency modular and scalable bioreactor designs for different waste water plants.

To optimize the mixed culture system for various applications, understanding yeast-microalgae interactions dynamics is necessary. Biomass composition needs to consider interaction mechanisms in order determine performance of this coculture system. Consequently, biomass produced by symbiotic relationship between yeast and microalgae is preferred for bio-lubricant and carotenoid production due to its better quality. Nevertheless, managing these dynamics over time poses challenges mainly in maintaining stable balance between the two species. Physiological shifts can lead to significant fluctuations on productivity if left uncontrolled for extended period hence leading to unstable conditions. Additionally, attempts have been made to incorporate adaptive traits into communities using synthetic biology.

Applications and Future Directions

The implications derived from our study findings will have an impact on different industries especially those involved with sustainable production and environmental management. Co-culturing strategies for bio-lubricants and carotenoids provide possibilities that do not rely on conventional resource-intensive techniques but rather align themselves with green chemistry approaches globally towards sustainable development goals. The incorporation of yeast-microalgae co-cultures in wastewater treatment can result in more efficient and sustainable treatment systems, thereby reducing the environmental burdens associated with this process. Nonetheless, despite such promising applications there still exist several shortcomings within our understanding of co-culture systems. Within these voids future study is expected to be carried out focusing on aspects such as process optimization, scalability or even integration with industry by-products. Conclusions from our systematic review indicate that yeast-algae mixed cultures are a versatile technology for multiple sectors including bio-lubricant and carotenoid production as well as water purification through sewage treatments. However, despite advances made in the current research on these technologies, further developments of bioprocess engineering, genetic modification and system integration are needed to exploit the full potential of co-cultures. Therefore, it will take more than just dealing with the identified challenges but also venturing into new areas that will help unlock their true potential towards achieving sustainable industrialization and ecosystems conservation through yeasts-algae symbiosis.

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