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Review

Solid state fermentation (SSF) on marine biomasses and their by-products - a new research biorefinery frontier for the obtention of innovative and novel value-added compounds towards industrial applications

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ABSTRACT

Solid-state fermentation (SSF) is a well-established biotechnological process for the valorization of agro-industrial residues, aligned with the circular economy and the principles of sustainability. While its application in agro-food sector is well documented, the potential to exploit sea industrial by-products (e.g., fish, shrimp, algae biomass, among others) to produce and develop high-value molecules. This review provides a critical overview of the current outlook and perspectives of SSF using sea by-products as alternative substrates form microbial development. By the incorporation of a bibliometric analysis (458 scientific articles, 2010 – 2026) it was revealed the upcoming growing interest on SSF field for sea by-product upcycling as well as nutritional and functionality enhancements of the end-products. In contrast, intellectual property screening (419 patents, 2023 – 2024) identified a significant gap (2 patents) on SSF applications into the sea-industry, leaving an ample umbrella in research and development for novel discoveries and innovations. Therefore, this review proposes sea by-products as a promising avenue for disruptive innovations under biorefinery approach to produce multiple and diversified biomolecules. The integration of SSF bioprocesses into biomasses refinery will not only contribute to circular economy principles but also will represent a strategic opportunity to unlock novel bioproducts with scientific and industrial relevance.

1. Introduction

In recent years, global challenges in health, food, energy, and social systems have been exacerbated by rapid population growth, leading to resource depletion and environmental degradation (Huo and Peng, 2023). Rising demands for food and materials highlight the need for sustainable, regenerative production methods. For example, Mkadem and Kaanane (2024) highlight the modest growth of 4.3% in sea production, reaching up to 223.2 million tons (animals and algae), while emphasizing the large amount of waste generated, up to 75% depending on the species. Thus, concepts like sustainable intensification aim to boost food output while preserving resources and ecosystems (Mendonça et al., 2023). Likewise, the circular economy has evolved from a crisis-response model (reduce, reuse, recycle, recover) into a regenerative strategy for sustainable development, environmental quality, economic growth, and social equity (Hartley et al., 2024; Kirchherr et al., 2023).

Under the “Sustainable intensification”, the Solid-state fermentation is a well-known biorefinery technology for the valorization of residues through recovery and production of bioactive compounds mainly from residual substrates such as cereals, fruits, vegetables, wine waste, among others (Cano y Postigo et al., 2021; Teigiserova et al., 2021) with the attractive benefits such as: absence or near absence of water (mimic the natural environment of fermentative microorganism), lower cost, higher production yields, easy technology, and lower water/energy requirements).

In the last 6 years, numerous studies (4935 articles, Scopus, 2020 – 2026, 08 April, 2026) have been successfully developed mainly in agro-

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industrial residues; however, a lower-explored area of potential substrates to be evaluated under SSF technology encompasses the sea-industry (458 articles, Scopus, 2020 – 2026, 08 April, 2026), which is one of the most demanding sectors of food production with the capacity to provide the 17% of the worldwide meat production (Costello et al., 2020). The relevance of sea-sector, together with the emerging growth of the circular economy within the maritime sector, represents an opportunity for the integration of bioprocessing technologies, which could provide the development of new products or the production of green materials. Additionally, valorization under SSF technology can be applied to fresh marine biomasses or by-products, addressing the issues related to the high number of discards associated with the high percentage of biomass that are not edible, such as scales, fish heads, and shrimp shells.

In this context, the aim of this review is to provide a comprehensive overview of SSF as a promising biorefinery approach for the valorization of marine biomass into value-added molecules and applications. This review seeks to consolidate and critically analyze the current state of research on the use of marine derived substrates in SSF processes.

2. SSF: A bioprocessing tool into circular bioeconomy trends

The “circular economy” is a concept that has been extensively studied in recent years in the scientific literature using multiple approaches (biotechnological, chemical, environmental, economic, and financial). Its definition includes an economy that aims the value creation from waste generation (Camacho-Otero et al., 2018; Hoof et al., 2024; Papamichael et al., 2023; van den Bergh, 2020). Nowadays, the generation of new employment opportunities and the protection of marine ecosystems have been highlighted due to the potential for creating new value chains through the valorization of sea waste (Ruiz-Salmón et al., 2020).

Therefore, current strategies have been developed with the fervent objective of finding new valorization strategies for multiple by-products that the sea industry generates. Following the Sustainable development goals (SDGs): (2) Zero hunger, (3) Good health and well-being, (9) Industry, Innovation, and infrastructure, (12) Responsible coemption and production, (13) Climate action and (14) Life below water. Some strategies englobe the innovative green technologies for the valorization of sea industry by-products (fish waste) (Khawli et al., 2019; Yuan et al., 2024; J. Zhang et al., 2023), highlighting the impact of ultrasonic extraction (UAE) and supercritical fluid extraction (SFE) technologies in the recovery of value-added compounds. Similarly, Cristina et al. (2021) highlight non-thermal extraction technologies for the valorization of crustacean processing by-products, such as supercritical fluids, high pressures, electrical pulses, and ultrasound.

However, it has been a marked interest in the implementation of biological methods using enzymes and/or microorganisms for valorization (Mabate et al., 2025; Venugopal, 2021). This biological approach is the cornerstone for the development of bioprocessing “Added value material production from a living source” (Cossar, 2011), such as biofuels (lipids, seaweed), bioactive products (peptides, phenolics and polysaccharides, algae, fish and shrimp), and biomaterials (chitin and chitosan, shrimp) (Ng et al., 2017), where SSF stands out for its sustainable advantages (low water and energy requirements).

Some remarkable microorganisms for SSF are filamentous fungi such as *Aspergillus* spp., *Trichoderma* spp., and *Fusarium* spp have been reported as potential producers of enzymes (endoglucanases, exoglucanases, peroxidases, among others) with the ability to degrade polymers in complex matrices (Haokok et al., 2023; Yafetto et al., 2023). And, some bacterial strains, from species such as *Lactobacillus* spp. and *Leuconostoc* spp.

Thus, the SSF englobes an alternative with a biological focus in the development of new sustainable strategies. The following sections will present by-products with potential for valorization through SSF, as well as some examples previously studied in recent years.

3. Marine biomasses as emerging substrates for SSF

The maritime industry produces enormous quantities of basic foods around the world (fish and seafood). Additionally, current trends seek to exploit new sources of beneficial compounds (health, food, or energy) in the sea (Prabha et al., 2019). Thus, it is currently possible to find a greater number of by-products (spent biomass) that could be the basis for novel bioprocesses, increasing the sustainability of pre-believed processes.

3.1. Shrimp shell

Shrimp is a crustacean of great interest in maritime gastronomy around the world, however, its consumption does not include the entire biomass it comprises, some parts, such as the shell, are considered waste despite being a valuable source of high-value molecules, including minerals, lipids, protein, vitamins, enzymes, and carotenoids, among others (Duppeti et al., 2023). It is essential to note that approximately three million tons of shrimp are caught annually, with around 30% of the catch considered waste (shell) (Liu et al., 2023).

In this context, the waste comprises approximately 50% protein, 20% chitin, and 30% minerals, with the potential to be considered a source of interesting molecules, including peptides and oligomers (Lu et al., 2023a). Nowadays, the valorization of these wastes and harvested biomasses (from other crustaceans) has been studied for the recovery of chitin derivatives, protein isolation, hydrolysate production, flavoring substances, lipid, and pigment isolation. The main technologies applied encompass microwave or ultrasound-assisted extraction (MAE/UAE), supercritical fluid extraction (SCFE), and pulsed electric field (with extractions yields between 20 and 30 %) (Z. Zhang et al., 2023). However, the use of SSF to explore this waste is scarce, with very few examples published. Although the biorefinery approach has primarily investigated chitin oligosaccharide production through chemical procedures, an alternative bioprocessing method involves breaking β-1,4 glycosidic linkages via SSF using actinomycetes to recover bioactive products (Widyastuti et al., 2022). Additionally, one approach to be elucidated involves the integration of microbial strains producing proteolytic enzymes (e.g., *Aspergillus* sp) that can trigger potential protein degradation and subsequent generation of potentially bioactive peptides.

3.2. Fish by-products (FBPs)

An attractive topic in the sea-food industry is fish waste management due to the higher environmental impact that fishery discards could aggravate; also, the fish waste could be a source of high-value molecules as collagen, gelatin, oil, peptides, hydrolysates or as substrate for enzymatic production (lipases, proteases, chitinases, among others). Additionally, Wangkheirakpam et al. (2019) defined the fish waste content as 58% protein, 19% fat and minerals, and 22% monounsaturated fatty acids, including palmitic and oleic acids. The high quantity of protein has made FBPs an interesting source of possible bioactive fractions, such as peptide hydrolysates. The current extraction of these bioactive fractions involves a hydrolysis step using enzymatic cocktails (e.g., Alcalase®, Flavourzyme®, Protamex®) from different microorganisms, such as *Bacillus licheniformis*, *Aspergillus oryzae*, and *Bacillus licheniformis* (Ortizo et al., 2023). For example, the obtention of antioxidant peptides from red tilapia (*Oreochromus* sp.) (Sierra et al., 2021). However, the application of purified enzymes (alcalase, papain, pepsin and pancreatin, 15 – 40 % yield according to the temperature, pH) encompasses a higher economic cost and an additional step in the conceptualization of the process in general (enzymatic acquisition) (Hopkins et al., 2025). Thus, fermentation could be an efficient technology using a natural procedure (Coppola et al., 2021), with the potential to produce other attractive molecules (e.g, mycoprotein). Its application in FBPs has been focused on liquid or submerged fermentations; therefore, scarce information is available concerning the use of the SSF process in FBS. This can be explained by the composition and nature of the waste, since animal by-products comprise a more complex chemical composition (fatty acids, protein, among others) and are susceptible to deterioration and potential microbial contamination (putridity). This is unlike by-products such as algae, which have a different chemical composition (complex polysaccharides) that hinder microbial degradation. However, stabilization methodologies (drying, autoclaving) can accompany the use of animal by-products. This presents an opportunity to pioneer innovative advancements in the field, aiming to uncover novel applications within SSF technology.

3.3. Seaweed

Seaweed plays a fundamental role in the aquatic ecosystem; their application in human diets is based on their nutritional contribution to human health as a reliable source of proteins, fibers, minerals, vitamins, and carbohydrates (Harb and Chow, 2022). The carbohydrate content can range from 2.67% to 73.2%, and the protein content could rise to 32.7%, depending on the species and growth conditions (Subbiah et al., 2023). Additionally, it is expected that in 30 years, seaweed will be the primary tool for meeting the world's food demand (Bhuyan, 2023). Thus, the importance of diversifying the possible applications of the material through new food development processes and/or the reevaluation of materials from seaweed comprises a pinnacle in scientific development in recent years. Under the blue biotechnology approach, Reboleira et al. (2021) established that seaweed is a promising substrate for biotransformation via the fermentation process to obtain new high-value molecules. Although the conventional biotechnological approach to seaweed valorization has primarily focused on the energy sector as a source of lipids for biodiesel production, current efforts have successfully implemented SSF technology to recover high-value molecules, such as polyphenols (Lee et al., 2022; Norakma et al., 2023). Another interesting approach involves the production of mycoprotein for both food and feed applications (Salgado et al., 2021), with prospects for developing alternative meat products.

3.4. Microalgae

Microalgae are among the most studied marine substrates in recent years. Its interest lies in the advantages of production, such as reduced non-arable land requirements, improved growth parameters, potential applications in seawater, and lower production space, among others, also, by its carbohydrate richness (amylose, amylopectin, floridean starch, glycogen, among other forms) (Garofalo et al., 2022), combined with other valuable molecules, such as polyphenols, carotenoids, proteins, pigments, and minerals. Primarily, research on microalgae utilizes the fermentation method as a pretreatment for biofuel production (Dębowski et al., 2022; Kusmiyati et al., 2023). In the food area, the application of fermentation in microalgae has been primarily explored through liquid and submerged technologies, utilizing lactic acid bacteria (LAB) and yeast. Currently, the application of *Lactobacillus plantarum* fermentation to *Arthrospira platensis* yields extracts with higher antioxidant activity than control. According to the authors, this approach could lead to the development of value-added food products (Jamnik et al., 2022)

Incorporating a fermentation step into microalgae biomass processing could yield benefits, such as the release of bioactive compounds from the initial microalgae biomass, including phenolics, bioactive peptides, or compounds related to microorganism metabolism. The reduction of complex chemical forms into simple structures with high digestibility, or the application of a fungal strain to produce mycoprotein, are other relevant opportunities in the food area. However, a potential challenge to overcome is particle size, since smaller biomasses tend to compact, hindering oxygen transfer and triggering surface growth. One solution is the integration of multiple substrates or the development of new bioreactor configurations to promote aeration and distribution of the microorganism throughout the biomass.

4. Technological comparison of solid-state fermentation: limitations and potential solutions

4.1. Sea by-products as substrates

In section 3, the sea by-products with potential application as substrates for solid-state fermentation (SSF) were shown. However, the distinct biochemical compositions of these substrates entail specific advantages and challenges that must be addressed to maximize their valorization (Table 1).

The first two substrates, shrimp shells and FBPs, originate from animal sources are primarily composed of proteins (<50%), lipids (up to 50%), chitin (in the case of shrimp shells, 20%), and other minor components. In contrast, seaweeds, and microalgae, which are of plant origin, exhibit markedly different chemical profiles, characterized by high carbohydrate content (structural polysaccharides, 20 – 60%) along with significant protein levels. These compositional differences determine distinct technological challenges and processing requirements for SSF.

For example, shrimp shells present significant challenges due to their high calcium carbonate ($CaCO_3$) and protein content, which hinder efficient chitin recovery and microbial accessibility. A conventional approach involves acid demineralization using strong acids (e.g., HCl), followed by extensive washing steps, which increase water consumption. Additionally, deproteinization is typically needed, often using enzymatic treatments (Younes et al., 2016). Alternatively, biotechnological strategies without pretreatment have been explored, such as the use of bacterial consortia, achieving up to 99.5 % protein removal (5 °C, 6×10^7 CFU/mL, 16 h) (Sirvas-Cornejo et al., 2024). Furthermore, Lu et al., 2023b highlighted the potential to recover calcium lactate (reaction of $CaCO_3$ with lactic acid) through SSF using *Streptomyces* sp. SCUT-3 for feed or food approach.

In the case of FBPs, key challenges include lipid oxidation and compositional variability. To address these issues, Dadkhodazadeh et al. (2024) proposed a stabilization strategy involving thermal treatment (cooking) for lipid removal, followed by drying and particle size reduction, and the incorporation of complex carbohydrate sources (potato pulp and malt beverage waste). The SSF was driven with lactic acid bacteria (*Lactobacillus planetarium*, *Lactobacillus fermentum*, and *Pediococcus acidilactici*), enabled the production of fermented biomass with enhanced protein content and digestibility. Nevertheless, in both cases, claiming a cold chain is essential to prevent unwanted microbial growth and contamination, as well as ensuring proper sterilization prior to SSF processes.

Other aspects to consider, which represent stress conditions for the microorganism, include minerals, salinity, and the presence of heavy metals. Higher concentration of minerals can trigger a high osmotic pressure in the membrane, slowing down the metabolite and causing death (recommended concentrations lower than 10-4 M) (Chen et al., 2022; Šelo et al., 2021). Similarly, salinity has been reported to have an inhibitory effect on the enzymatic activity of lactic acid bacteria metabolism in broad bean paste meju fermentation (H. Li et al., 2023), and potentially on other microorganisms as well. Although one strategy could be washing the residual biomass, this would increase the water demand of the process and compromise its sustainability. An alternative approach would be the use of strains known to be resistant to saline conditions. For example, Han et al. (2025) highlighted the potential of *A. oryzae* due to its ability to withstand high salt conditions, offering advantages as a chassis for expressing marine enzymes. On the other hand, the presence of heavy metals in the by – products could inhibit microbial activity and reduce substrate bioconversion or utilization. Moreover, their potential bioaccumulation would limit applications in the food sector (Barrera-León et al., 2025), shifting their valorization

Table 1
Comparative analysis of sea by-products for solid-state fermentation: Composition, advantages, limitations, and pretreatments.

By-products	Main components	Advantages for SSF	Limitations for SSF	Typical pre-treatments	Potential Applications
Shrimp shell	Protein (50%) Chitin (20%). Minerals (30 %)	High-value chitin-derived products. Bioactive peptides. Production Enzymes	Requires specialized enzymes (chitinases). High mineral content. Guarantee cold chain until bioprocessing Sterilization step	Demineralization, Deproteinization.	Chitosan Bioactive oligosaccharides Enzymes
Fish by-products (FBPs)	Protein (58 %) Fat and minerals (19%)	High protein content. High peptide production	Lipid oxidation. Variability in composition. Potential microbial contamination. Guarantee cold chain until bioprocessing. Sterilization step	Lipid remotion Homogenization Sterilization	Bioactive peptides Animal feed Protein hydrolysates
Seaweeds	Carbohydrates (2.67 - 73.2 %). Protein (32.7 -50 %)	Higher carbon source (Carbohydrates) Bioactive compounds recover Lowe susceptibility to microbial contamination	Complex polysaccharide matrix; Specific enzymes (e.g., cellulase and alginate lyase) Sterilization step	Particle size reduction Drying process	Enzyme production Bioactive extracts (Polyphenols) Fermented biomass production (Seaweed and mycelium)
Microalgae	Protein (30 - 60 %) Carbohydrates (20 - 30 %) Lipids (6 - 8)	Higher carbon source (Carbohydrates) Lowe susceptibility to microbial contamination	Rigid cell wall. limited bio accessibility. Complex polysaccharide matrix; Specific enzymes (e.g., cellulase and alginate lyase) variability depending on species and cultivation Sterilization step	Cell disruption (Fresh biomass), enzymatic hydrolysis, Drying process	Enzyme production Bioactive extracts (Polyphenols) Fermented biomass production (Seaweed and mycelium)

toward other alternatives such as biochar production.

The algae derived by-products present challenges associated with the structural complexity of their cell walls. Therefore, the selected microorganisms must be oriented to the enzymatic machinery required to degrade polysaccharides such as laminarin, cellulose, fucoidans, and alginates. Filamentous fungi, including *Aspergillus*, *Rhizopus*, and *Trichoderma*, are well known for their hydrolytic capabilities and enzyme production (cellulase, laminarinase, and alginate lyase), making them suitable candidates for SSF of these substrates (Agabo-García et al., 2025). In the specific case of microalgae, their small particle size is an added challenge, as it promotes aggregation and may lead to anaerobic conditions that hinder microbial growth. As a result, co-fermentation strategies involving the blending of microalgae with other agro-industrial by-products have appeared as a promising approach to improve substrate structure, enhance aeration, and provide added nutrients or bioactive compounds, thereby improving overall process performance.

In summary, the use of sea by-products as substrates for SSF requires strategies tailored to their biochemical composition and structural complexity. Therefore, the integration of pre-treatments, microbial choice, and substrate formulation is essential to enhance process efficiency and support the sustainable valorization within a circular bioeconomy framework.

4.2. *Fermentation strategy: different valorization approaches (submerged, liquid, and solid fermentation)*

The fermentation, as a biotechnological strategy, can be broadly classified into 2 categories based on the operational mode: submerged-liquid state (SmF) and solid-state fermentation (SSF).; the submerged fermentation involves the cultivation of microorganisms in a liquid culture medium where nutrients are dissolved, resulting in the production of microbial biomass and extracellular metabolites dispersed in the medium (Yan et al., 2023). Additionally, SmF systems may incorporate suspended solid substrates in the form of slurries, expanding their applicability to heterogeneous feedstocks (Yousefi et al., 2025).

Otherwise, SSF is characterized by low or near absence of free water (capillary water may still be present), this feature provides several advantages, including lower water and energy requirements, as well as enhanced production of enzymes and secondary metabolites (Mattedi et al., 2023; Yousefi et al., 2025). A comparative overview of both strategies is presented in Table 2. Notably, SSF operates at lower moisture levels, which can limit the growth of microorganisms with high water requirements (e.g., bacteria). Conversely, SmF operates with higher water contents (liquid media) and englobes a higher contamination risk. One of the main differences between SSF and SmF is that

Table 2
Solid-state and submerged fermentation for sea by-product valorization.

Parameter	Type of fermentation strategy		Implications for sea by-products
	Solid-State Fermentation (SSF)	Submerged Fermentation (SmF)	
Moisture content (%)	12 – 70	>90	SSF (Higher moisture range) SmF (Higher moisture content and liquid media)
Type of substrate	Solid (insoluble)	Soluble/ suspended	SSF = Insoluble substrates (Structural complex) SmF = Soluble fractions
Oxygen transfer mechanism	Diffusion through matrix	Controlled aeration	SSF suitable for filamentous fungi SmF for bacteria/ yeasts
Process control	Limited	High (pH, temperature, CO_2, O_2, agitation,	SSF: Higher development at laboratory scale SmF preferred reproducibility and industrial scale
Water & energy	Low	High	SSF advantageous for sustainability SmF: Higher operation cost
Contamination risk	Lower (lower moisture levels)	Higher	SSF more robust for waste substrates SmF: Higher contamination risk due to the higher water content.
Pre-treatment needs	Often required	Often required	SSF and SmF: demineralization and hydrolysis
Industrial maturity	Emerging	Established	SmF dominates industry SSF growing technology in biorefinery framework

SmF allows for precise control of key operational parameters such as temperature (via heating/cooling systems), pH (through acid/base addition), and aeration (via gas injection), while also ensuring improved mass transfer in the liquid medium (Kalaiselvan et al., 2025). These features facilitate process optimization, reproducibility, and stability, explaining the widespread industrial adoption of SmF technologies (Mittal and Kushwaha, 2025). However, it could enable higher operational costs due to the need for advanced equipment (e.g., sensors, bioreactors, and control systems).

In contrast, SSF remains a well-established approach at the laboratory scale, commonly performed in simple systems (flasks, petri dishes, and aluminum trays) due to its low operational requirements. However, this simplicity is often associated with challenges in process control, particularly regarding temperature, pH, and moisture gradients. Despite these limitations, several reactor configurations have been developed to scale up SSF processes, including tray bioreactors, packed-bed bioreactors, stirred drum bioreactors, and rocking drum systems (Mattedi et al., 2023). Another important aspect to consider is the need for substrate pre-treatment. In most cases, an initial sterilization step is required to reduce microbial load and prevent contamination; however, this depends on the nature of the substrate and specific process requirements, such as the removal of antimicrobial compounds that may inhibit microbial growth. Rather than competing approaches, solid-state and submerged fermentation should be considered complementary strategies within integrated biorefinery frameworks.

Particularly, in the context of marine industries, solid by-products such as shrimp shells, fish viscera, and macroalgae represent promising substrates for SSF, particularly for the valorization of complex and insoluble fractions through the enzymatic activity of microorganisms adapted to low-moisture environments (e.g., filamentous fungi), with advantages in terms of reduced water and energy consumption. Nevertheless, SmF remains a more mature and widely implemented technology at the industrial level due to its superior process control and scalability. Despite this, SSF is gaining increasing attention as a sustainable alternative, particularly in the development of resource-efficient and circular bioprocessing strategies.

5. Current scientific efforts: extractive bioprocessing technology and biotechnological production system

The SSF represents a biotechnological strategy to use the microbial enzymatic machinery to extract or produce value added compounds, and the enhancement of nutritional properties. In the following section, we provide an overview of the current applications of SSF using sea biomass.

5.1. *Extractive bioprocessing technology*

The fermentation technologies have been highlighted as promising alternatives for bioactive compounds extractions due to the use of enzymatic machinery of microorganism to release compounds to the media (Si et al., 2023). For example, in sea-industry the fermentation (mainly SmF) increases the bioactivity and nutritional value of algae biomass (Zhipeng Li et al., 2023; Paredes-Comacho et al., 2023; Pérez-Alva et al., 2022); taking advantage of the rich sources of nutrients and bioactive compounds, making them suitable substrates for the development of SSF technologies (Subbiah et al., 2023; Zhao et al., 2023).

Additionally, available information has demonstrated the positive potential of SSF technology in marine biomass. For example, the application of *Monascus* spp. in algae has shown several benefits, including enhanced bioactivities. Its application in *Saccharina japonica* and *Undaria pinnatifida* has shown a polyphenolic content enhancement, with inhibition of α-amylase and α-glucosidase (Suraiya et al., 2018a). Similarly, a subsequent study conducted with *S. japonica* using *Monascus* spp showed a bioactive improvement, as well as higher a free amino acids content in the hydroalcoholic extracts (Suraiya et al., 2020). A well-known species from *Aspergillus* spp, *Aspergillus oryzae*, has been applied in SSF process (*Kappaphycus* spp., red algae) showing an increase in the content of caffeic acid (relevant phenolic compound), volatile compounds and glutamic acid (Norakma et al., 2021). Other positive results were showed in three red algae (*Kappaphycus* spp.) for the enhancement of phenolic compound extraction with *A. oryzae*; the obtained data showed an increase in antioxidant activity resulting from the enzymatic metabolism of the fungal strain (Norakma et al., 2023). Also, a novel approach is the multi-recovery of valuable molecules as in the efficient *Streptomyces* SSF-plus-lactic acid method developed for the valorization of shrimp shells capable of recovery free amino acids, oligopeptides, calcium (as calcium lactate), and chitin (Lu et al., 2023c).

However, in a study carried out by Martelli et al. (2020) using strains of *Lactobacillus* sp and *Bacillus subtilis* in *Himanthalia elongata* (brown seaweed) showed a decrease in polyphenol content from 2.94 to 0.20 gallic acid equivalent per gram; this reduction highlights that fermentation was not an appropriate technology for the recovery of these bioactive compounds in that specific substrate, possibly due to the lack of optimization of parameters such as particle size, pH, moisture content, and inoculum size, which affect microbial growth, metabolic activity, and the potential release of bioactive compounds into the medium for their recovery; opening an opportunity to search new conditions to incorporate SSF technology successfully.

Therefore, it is essential to conduct new research studies that explore the development of novel microorganisms and optimal operational conditions to solidify the technology in marine substrates, highlighting a research opportunity for the years to come.

5.2. *Biotechnological production system*

5.2.1. *Enzymatic production and bioproducts*

A relevant approach of SSF involves the recovery of enzymes produced by microorganisms for industrial applications; even companies such as Aumenzymes® specialize in the production of industrial-grade enzymes produced by solid-state fermentation and submerged fermentation, which provides a potential interest in the search for new substrates (by-products) for enzyme production.

Considering marine biomasses studies, the application of fungal strains of *Aspergillus ibericus* MUM 03.49 and *Aspergillus niger* CECT 2915 was explored into seaweeds species (5 species), and the results showed a difference between the production of enzymes (xylanase, cellulase and β-glucosidase) according to the microorganisms and the species implemented as substrate (Ferreira et al., 2022). Additionally, the evaluation of SSF for alginate lyase production was assessed in *Sargassum* spp. Using *Cunninghamella echinulata* to promote alginate degradation. Its application showed that moisture content increased production, and an inducer (sodium alginate) increased production from 175 to 200 U/mL (Dos Santos Silva et al., 2022). Similarly, the use of *Sargassum* to produce enzymes was explored by the incorporation of seaweed into SSF of cow dung using a *Streptomyces* sp Alg-S23 strain to produce alginate lyase and mannanase in a co-produced via SSF process (Mohapatra, 2021).

Based on the examples, a potential recovery of various enzymes from SSF in marine by-products has been suggested; however, it is essential to note that the chemical composition of the substrate will have an impact on production. For example, Ma et al. (2024) indicated that cellulase production involves a mechanism induced by the carbon source (glucose and cellulose). Thus, substrate/microorganism/target product selection work will have to consider these aspects.

5.2.2. *Added-value molecules beyond enzymes*

Another novel approach for SSF englobes the production of non-enzymatic molecules as: safe pigments, novel flavoring agents, natural bioactive compounds, and alternative protein sources (mycoprotein) which respond to the growing rejection of synthetic counterparts and the search of novel food sources according to the growing population.

5.2.2.1. Pigments production. Under natural pigments search, a few articles have explored the potential of sea by-products as a substrate through the SSF. However, the seaweed biomass (*Saccharina japonica*) was explored as substrate for SSF by *Monascus* spp; it reached a (monascin, ankaflavin, rubropunctatin and monascorubrin) yellow/orange pigment's production of (83.01 U/gram fresh substrate) with higher stability, demonstrating a possible new source of natural pigments from sea by-products (Suraiya et al., 2018c). Additionally, another possible indirect approach for pigment production includes the SSF applications as a booster nutritional composition substrate; in a study carried out by Kim et al. (2023), a fungi strain was applied in the SSF process for the enhancement of the nutritional properties of okara by-product to pigment production process by *Phaeodactylum tricornutum*, a marine microalga with the capacity to produce flucoxanthin (pigment); the SSF increase the pigment production by twofold. Thus, pigment production represents an interesting application of SSF in utilizing marine biomass.

5.2.2.2. Flavoring production. Another application of interest includes the production of natural flavorings. For example, vanillin is a component that has been produced in recent studies by the bacterial strain *Bacillus aryabhattai* NCIM 5503 through a SSF process using coconut by-products (Paul et al., 2023). Only a few studies have been exploring the use of SSF technology in marine biomasses; however, the production of food additives such as "erythritol" (a low-calorie sweetener) was explored by Liu et al. (2021), In this study, a hydrolysate was produced from the microalgal *Schizochytrium* residue using a yeast strain (*Yarrowia lipolytica* M53-S) in a Fed-and-repeated batch process. They produced 205.4 mg erythritol/gds or 20.54 g/100gds (grams dry substrate), a higher value than the production reported in *Bacillus aryabhattai* NCIM 5503 using coconut (0.528 g/100 g dried raw material of coconut coir) (Paul et al., 2023). Thus, it proves to be an alternative for the market of new sweeteners.

5.2.2.3. Bioactive compounds production. Another interesting approach for SSF englobes de production of metabolites and bioactive compounds, for example, the SSF process using *Monascus purpureus* on *Saccharina japonica* (brown seaweed) could produce lovastatin (auxiliary in inhibition of cholesterol biosynthesis) at a concentration of 13.40 mg/g dry substrate, with the potential to be applied in the food and pharmaceutical industry (Suraiya et al., 2018b). Otherwise, a well-studied by-product for bioactive production englobes shrimp shell with actinomycetes. A crude fermentative extract obtained from Shrimp shell waste using *Pseudonocardia carboxydivorans* by Setiawan et al. (2021) showed antifungal capacity, reporting 74% growth inhibition against *Malassezia globose* (dandruff). Complementary, the isolation of fifteen actinomycetes showed ten strains with antimicrobial compounds production against Multiresistant *Staphylococcus aureus*. The authors attributed this efficiency to the strain's capacity (*Pseudonocardia carboxydivorans)* to produce antimicrobial metabolites such as Branumycin B (Setiawan et al., 2021). Also, another study carried out by Laila et al. (2023) validated the potential of actinomycetes (*Streptomyces tritolerans*) and SSF technology for the recovery of bioactive extracts, with antimicrobial activity against *S. aureus* and *M. globose* related to the possible presence of alkaloids. Finally, the antimicrobial potential encompasses a potential alternative in the search for new natural antibiotics to address the urgent global public health related antimicrobial resistance according to the CDC (Center for Disease Control and Prevention) (Thawabteh et al., 2023).

5.2.3. Mycoprotein production

Nowadays, alternative proteins (algae, insects, and fungi) have gained attention in the industry due to their benefits, particularly the "Mycoprotein" has become popular due to its advantages such as low costs, high nutritional value, ecological protection and by-product valorization, even its application has been identified as the next frontier of the food industry (Majumder et al., 2024)

Recent studies on marine biomasses have been focused on SSF. Thus, studies such as the one conducted by Gordillo Sierra et al. (2022) applied an SSF process to promote the valorization of *Sargassum* spp by the application of *Aspergillus oryzae* to improve nutritional properties. The study showed an increase in protein content up to 6.5% and showed an additional benefit, the reduction of heavy metal concentration. A similar behavior was reported by Loaiza et al. (2022) who observed an increase in protein content of 6.6% (96 h) in *Sargassum* spp. using *A. oryzae* in a packed-bed bioreactor configuration.

Otherwise, Ochogavias et al., 2026 evaluated the potential of other sea by-products (mussels, tuna, *Ulva rigida*, and *Saccharina latissima*) using the GRAS strain *Rhizopus oligosporus* CECT20169, demonstrating an increase of up to 27% (70.24 $\pm$ 2.64%) compared to the initial content, along with changes in the amino acid profile and a potential modification of sensory attributes.

Thus, the search for alternative protein sources could be explored through marine biomasses and SSF technologies to produce novel and "up-cycled" food products (Table 3) to prevent food waste by creating new, high-quality products out of surplus/residual food (Fig. 1).

6. General safety aspects in the SSF process

SSF technology shows promising results in bioactive metabolites production and recovery with health or industrial potential; however, ensuring their safety for human and animal use remains a key consideration. Although fermentation has been used since ancient times to enhance the nutritional value and microbiological stability of foods (soy sauce, tempeh, and kimchi); some fermented products have also been associated with the potential presence of harmful substances, either from microbial metabolism or because of the transformation of matrix components into toxic forms.

As microbial metabolites, the mycotoxins comprise products of fungal metabolism with potential adverse effects on human health, the filamentous fungi of the genera *Fusarium*, *Penicillium*, *Alternaria* and *Aspergillus* are mainly referred to as producers of mycotoxins, some mycotoxins found predominantly in fermented foods include aflatoxins, fumonisin, zearalenone and deoxynivalenol (Roy et al., 2023); the mechanisms of action and harmful effects vary according to the type of mycotoxin (vomiting, fever, hormonal imbalances, DNA damage, cancer, immune suppression, and even death). Otherwise, biogenic amines (BAs) comprise a group of substances produced by the microbial decarboxylation of free amino acids or amination/transamination of aldehydes and ketones, such as histamine, putrescine, and tyramine, among others (Owolabi et al., 2022; Schirone et al., 2022; Tırıs et al., 2023). Low concentrations of these substances do not pose a serious risk to human health, unlike high doses, which can cause hypertension, gastroenteritis, headaches, fever, vomiting, and other adverse effects (Tırıs et al., 2023). However, it is important to emphasize that not all species within the genera *Fusarium*, *Aspergillus*, and *Rhizopus* have the potential for mycoprotein production (e.g., *Aspergillus niger*, *Aspergillus oryzae*, *Rhizopus oryzae*, *Fusarium venenatum*, *Rhizopus oligosporus,* among others). Therefore, the selection of the species to be used represents a critical step to ensure the safety of both the bioprocess and the final product (Gnaim et al., 2025; Massa et al., 2024; Singh and Gaur, 2021).

Currently, the detection of these undesirable molecules (e.g., BAs) is possible using well-known techniques such as: Chromatographic technologies (HPLC, UPLC, GC) coupled with UV-visible or MS (mass spectrometry) and ELISA (Tırıs et al., 2023). However, in the search for economical options with a lower complexity, techniques as: "fluorescent sensors" with high selectivity have been developed (Ziyong Li et al., 2023). Similarly, for mycotoxins detection, the biosensors can utilize biomolecules (DNA, enzymes, microorganisms, antibodies, etc.) as elements that enhance the test's sensitivity in a specific reaction between the mycotoxin and the antibody or aptamer (Chen et al., 2023; Fan et al.,

Table 3
Recent advances in the application of SSF to marine biomasses.

Microorganism	Class of microorganism	Subtrate	Growth conditions	Target Product	Relevant Results	Technological field	Reference
Yarrowia lipolytica M53-S	Yeast	*Schizochytrium* hydrolysate residue (SRH)	500 g PS medium, Inoculum size of 15% (5.0×10^4 cells/gds), and initial moisture at 70% and 30 °C	Erythritol production	The optimized condition reached an erythritol production (19.05 g/gds) using 4% biochar and 20% SRH. The implementation of the Fed-and-repeated-batch process increases erythritol production (20.54 g/gds) and cell viability (22.32 gds/g).	Bioactive compounds production	Liu et al. (2021)
Actinomycetes	Bacteria	Shrimp shell waste	200 g of substrate 200 mL (5.3×10^6 CFU/mL). 32 °C for 14 days	Antimicrobial metabolites	An actinomycete strain identified as *Pseudonocardia arboxydivorans* showed a lower minimum inhibitory concentration (250 μg/mL) to inhibit *Staphylococcus aureus*, and this activity could be related to the production of an analogue of branumycin B.	Bioactive compounds production	Setiawan et al. (2021)
Pseudonocardia antitumoralis 18D36-A1	Bacteria (Actinomycetes)	Shrimp shell waste	50 g shrimp shells, 25 mL, 1% inoculated liquid colloid medium, 6 days	Chitooligosaccharides production	The crude fermentative extract showed antifungal activity against *Malassezia globosa* (fungus) with an inhibition of 43%; the fractions D36A1C37 (69%) and D36A1C38 (74%) showed the most potent inhibition at the same concentration (1 mg/mL).	Bioactive compounds production	Widyastuti et al. (2022)
Actinomycetes	Bacteria	Shrimp shell waste	50 mL (1% colloidal chitin liquid medium) was inoculated with the strain. 100 g shrimp shells 14 days	Bioactive metabolites production	The strain 19B19A1 (*Streptomyces tritolerans*) showed antibacterial and antifungal activity *against Staphylococcus aureus* and *Malassezia globosa*. The extracts recovered from 19B19A1 strains contained alkaloids (indoles, diketoipiperazines, among others), which could confer bioactivity.	Bioactive compounds production	Laila et al. (2023)
Aspergillus oryzae	Fungus	*Sargassum* spp.	1×10^6 spores/g 6 g of *Sargassum* spp (pretreated at 170 °C), 30 °C, and moisture 70%	Green Bioprocess development	The SSF technology achieved a higher protein content at 96 h, reaching 6.6%. Also, the levels of heavy metals (antinutritional elements) decreased.	Improve nutritional properties	**Bonilla-Loaiza et al., 2022**
Aspergillus ibericus MUM 03.49 *Aspergillus niger* CECT 2915	Fungus	5 Seaweeds (*Gracilaria* sp., *Porphyra dioica*, *Codium tomentosum*, *Ulva rigida*, and *Alaria esculenta*)	5 g of substrate Moisture 75% 1×10^6 spores/mL 25 °C for 7 days	Xylanase, cellulase and β-glucosidase production	The result showed the higher production of xylanase 327 ± 40.04 U/g dry substrate (*A. niger*: *U. rigida*), Cellulase 124 ± 0.16 U/g dry substrate (*A.niger*: *G. gracilis*) and β-glucosidase 27.5 ± 1.48 U/g dry substrate (*A. ibericus: U. rigida*). Additionally, the protein content of *C. tomentosum* and *U. rigida* increased after SSF with *A. ibericus*.	Enzyme production	Ferreira et al. (2022)

Abbreviations: PS medium: peanut and sesame growth medium, gds: gran dry substrate, SSF: solid state fermentation, U/g: enzyme activity unit per gram, CFU: cellulase filter paper activity.

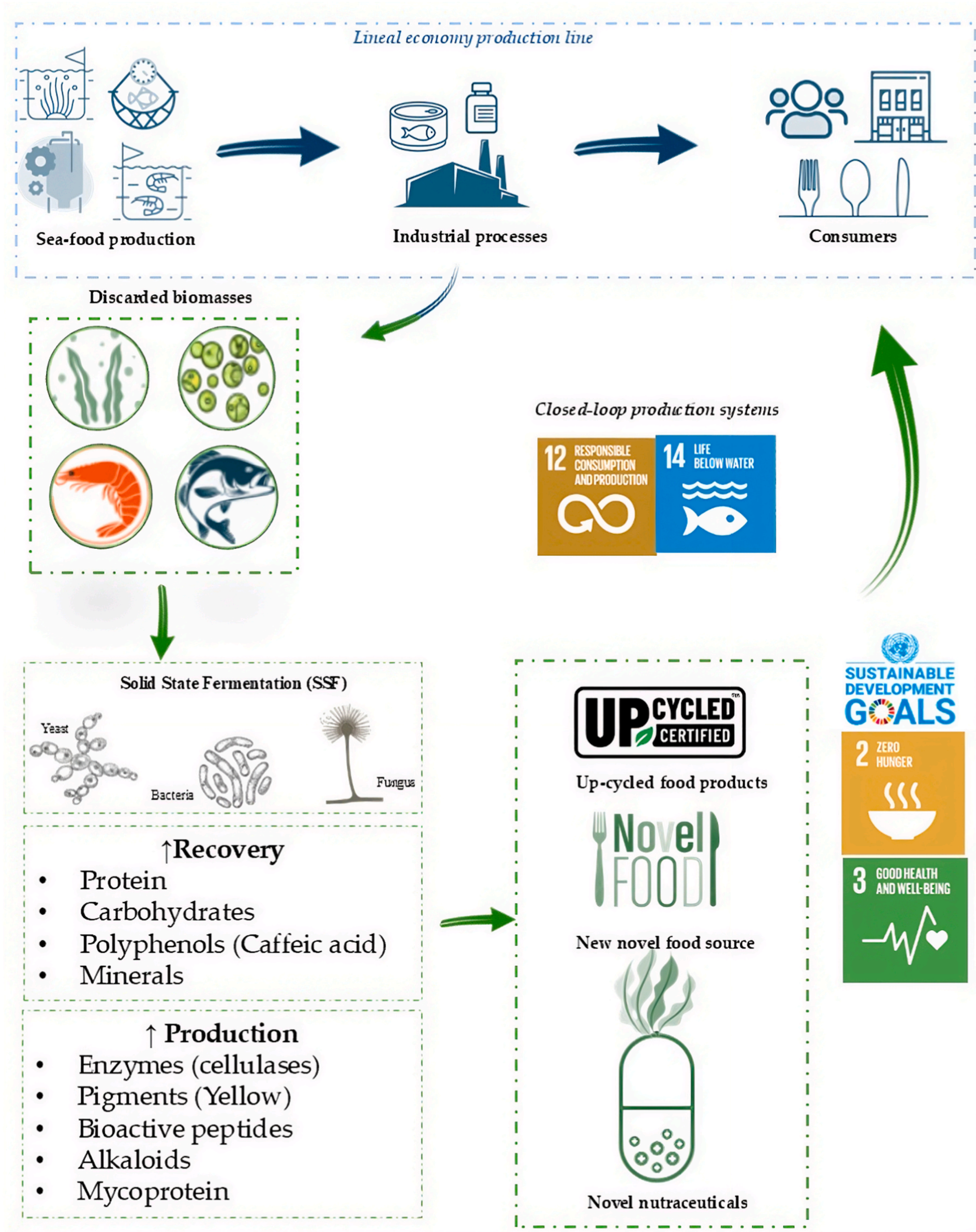

Fig. 1. Representative diagram illustrating the potential of SSF for the valorization of marine biomasses as an extractive and productive bioprocessing technology.

2023). Complementary, other strategy to guarantee the safety advantages of biological detoxification of mycotoxins using yeasts (*Saccharomyces cerevisiae*) or bacteria (*Rhodococcus erythropolis*) (Dey et al., 2023).

Current approaches prioritize the use of safe, GRAS strains. Fungal strains recognized as food-grade or edible by regulatory agencies such as the EFSA (EU) and FDA (USA) offer a promising basis for developing safer bioprocessing methods; because the GRAS status is granted only to microorganisms for which scientific evidence evaluated by qualified experts demonstrates safety under specific production and application conditions. The industrial integration of GRAS fungal strains has permitted the development of meat analogue companies, such as Quorn (https://www.quorn.co.uk/) or American Nature's Fynd (https://www.naturesfynd.com/fy-protein) (Gastaldello et al., 2022). Thus, scientific developments involving the application of safe and edible microorganisms comprise an area of potential growth for the upcoming years.

7. Intellectual property landscape: SSF applications on marine biomasses in food science

In the previous section, the summary of the current research efforts gave an actual perspective of SSF technology in marine biomass. However, the generation of intellectual property is a critical aspect for exploiting scientific value and facilitating the commercialization of technologies. Many investigations fail in making technological leaps,

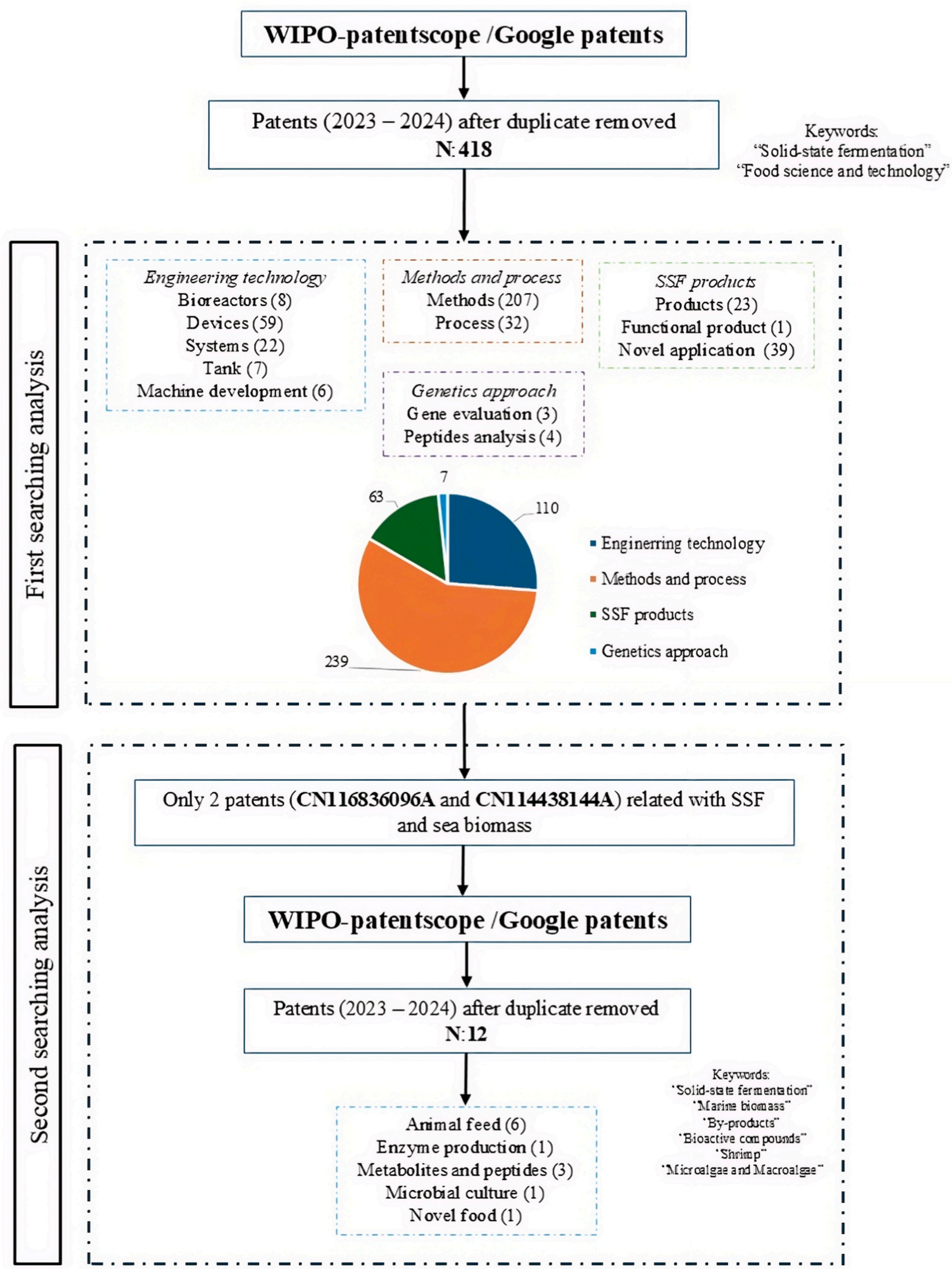

Fig. 2. Representative graph of searching procedures of patents published during the period from January 1, 2023, to July 28, 2025, on the topic of solid-state fermentation in food science and technology, and patents published in the period from January 1, 2023, to July 28, 2025, in marine biomasses.
Sources: Google patents and WIPO-Patent scope databases *(Accessed 28*th July 28, 2025*)*

often remaining confined to laboratory scale. Therefore, a complete intellectual property analysis for SSF technology was conducted using the information published in (January 1, 2023, to July 28, 2025) the "Wipo-Patentscope" and "Google patents" databases, to provide a current visualization of the SSF technology research area.

The first screening (Fig. 2) was conducted using the keywords "Solid-state fermentation" and "Food science and technology" to identify potential current areas for technological development in SSF that could be applied to marine biomasses. The filters implemented were: (i) Language English; (ii) Stemming activated (search according to the stem or root form), (iii) One Single Family Member, (iv) Not include non-patent literature.

The results showed a total of 419 patents published in 2023 - 2024, divided into 4 Clusters who were categorized according to their current technological interest in SSF (Engineering technologies, Methods and procedures, SSF products and Genetics).

1. The "Engineering technologies" cluster (110 patents), which encompassed patents related to the components (reactors) that enable the development of SSF, or provide solutions for operational problems (heat distribution, oxygenation, and operation controls).
2. The second cluster (239 patents), "Methods and procedures". The section focused on the SSF process methods, including growth conditions, extraction processes of bioactive metabolites, and the product development process.
3. The third cluster "SSF products" (63 patents) includes products made under the development of SSF technology such as: wines, fermented tea bags, secondary metabolites, and extracts.
4. The fourth cluster, "Genetics" (7 patents) includes the intellectual information generated in the evaluation of DNA, RNA or protein expression, and analytical methods that do not develop a commercial product.

The higher number of patents in "Engineering technologies" could be explained by the challenges into bioreactor architecture (substrate mixing, moisture control, temperature, aeration, pH, sensors) and parameters that must be optimized to improve the SSF. Recently, Sentís-Moré et al. (2023) have highlighted that a limiting factor is the lack of knowledge available on the design and operation of SSF bioreactors, especially in large-scale applications. However, there are currently reactors in different configurations aimed at addressing these challenges, such as tray, packed-bed, rotating drum, and fluidized-bed systems, which can be used. At present, these systems are being improved through the integration of sensors and specific combinations of configurations. Thus, novel studies related to SSF should focus on the aforementioned areas to expand current technological approaches.

Otherwise, it is important to highlight that according to the first analysis only two patents related with marine biomasses were published in 2023; the first one (**CN114438144A**) enclose a method for the production of oligopeptides, calcium lactate, and chitin from shrimp shell using SSF, and the second one (**CN116836096A**) discloses a process using *Streptomycete* marine strain for the production of 5 thio-benzoate compounds with anti-inflammatory activity in a rice solid culture medium. This limited number of patents may reflect the early-stage development of SSF applications for sea biomass, as well as existing industrial and economic constraints associated with scale-up, process standardization, and operational control in solid-state systems (Mattedi et al., 2023). These challenges can hinder the transition from laboratory research to commercially viable processes, despite the recognized potential of SSF for marine biomass valorization.

Thus, the lower number of produced patents indicates a novel opportunity area for the development of research projects to create new models, products, processes, and knowledge in SSF technology applied to marine biomasses.

7.1. *Intellectual property in marine biomasses: SSF in food science and technology*

Since the obtained data described in the previous section showed just two published patents regarding marine biomasses under SSF bioprocessing, a new search (Fig. 2) was made into the same databases with the application of specific keywords "Solid -state fermentation," "Marine biomasses," "Microalgae and Macroalgae," "By-products," "Bioactive compounds" and "Shrimp": within an interval of 2019 – 2024. The published information showed that twelve patents were published, five patents englobes the application of SSF into marine biomasses for the production of fermented products (**CN115886210**) as fermented sea cucumber with an improved organoleptic characteristics; also, for animal feed, its incorporation increased the quality of eggs (**CN113519717**), or the SSF technology developed enzyme (**BR1020024620A2**) higher nutritional content (**CN114532460A**) and improved digestibility (**CN109170130**, **CN114145389** and **CN112136987**), also, the SSF was applied into bioactive fractions such enzymes (**BR1020024620A2**), metabolites (**CN116836096A**) and peptides fractions (**CN114438144** and **CN112852909**). However, other applications, such as the production of microbial cultures (**CN109198176**) or the development of novel food products, like vinegar powder, have explored the incorporation of lactic acid bacteria and yeast (**CN109266507**). In Table 4, we summarize the technological disruptive patents according to an agro-food industrial approach.

Despite the low number of patents registered in recent years, it is essential to view the lack of patents as an opportunity area for technological development; the obtained results in recent SSF research (marine biomasses) and support of years of SSF research (on other by-products) offers valuable insights into the nutritional benefits and potential biotechnological applications that technology can provide, particularly in light of recent developments in the circular economy and the reevaluation of waste. Particularly considering recent developments in the circular economy and the valorization trends.

8. Trend analysis in scientific databases (SSF technology in marine biomass) by VOS-viewer

Nowadays, the continuous development of novel literature on SSF has led to the publication of numerous research studies, which offer insights into current trends in these technologies. Using specialized software for constructing and visualizing bibliographic networks (*VOS-viewer*), it was possible to identify and analyze current approaches in scientific databases over the past few years.

The data collection was performed using the keywords "*Solid-state fermentation*" and "Marine biomass" in the *Scopus* database by Elsevier (https://www.elsevier.com/products/scopus), considering only research articles published between 2020 and 2026 (accessed April 08, 2026). A total of 3066 documents published between 2020 and 2026 were identified. The articles primarily focused on the valorization of agro-industrial by-products were excluded, retaining only those focused on the valorization of marine biomass (458 documents). Subsequently, *Vosviewer* software (version 1.6.20) was used to perform a co-occurrence analysis of keywords by creating a thesaurus file to eliminate repetitions, synonyms, and plural forms (e.g., solid-state fermentation, solid state fermentation; antioxidant, antioxidants).

Additionally, the analysis enabled the classification of the information into eight distinct clusters (Fig. 3A and B).

- ***Cluster 1 (Average publication year 2024, red) "Functional applications & animal nutrition":*** The cluster encompasses studies detailing the application of SSF to enhance the nutritional value of marine by-products, particularly for animal feed and functional compound production. Main keywords: antioxidants, animal feed, growth performance, probiotics, amino acids.

Table 4
Novel patents in SSF for marine biomasses under a food science and technology approach.

Patent number	Title	Main core	Scope	Publication data	Country
CN113519717	Compound feed additive and feed for laying hens in the growing period	The invention relates to a compound feed for laying hens. The preparation method comprises mixing shrimp shell powder, bran, and glucose, adjusting the water content, inoculating *Phellinus igniarius* hyphae into the mixture, and performing solid-state fermentation to obtain a fermented material. The fermented material is then dried and crushed to obtain the feed.	Feed	22/10/2021	China
CN109170130A	The method of solid-state fermentation of aquatic products' leftovers prepares fish meal.	The invention expands the methods for preparing fish meal from the solid-state fermentation of leftover aquatic products. This process utilizes a microbial fermentation method to prepare fish meal.	Food improvement	08/02/2022	China
CN116836096A	Thiobenzoate compound, preparation method, and application thereof	The application encompasses five thiobenzoate compounds or their pharmaceutically acceptable salts. The five thio-benzoate compounds disclosed by the application can be obtained by purifying the fermentation culture (*Streptomyces* sp).	Bioactive fraction production	03/10/2023	China
CN114438144A	Method for producing amino acid, oligopeptide, calcium lactate and chitin by treating shrimp shell waste through streptomyces solid state fermentation and application thereof	The invention discloses a method for producing amino acids, oligopeptides, calcium lactate, and chitin by treating shrimp shell waste through solid-state fermentation (using Streptomyces) and its application.	Bioactive fraction recovery	22/09/2023	China
CN109266507A	A kind of preparation method for health-preserving vinegar powder	The invention discloses a preparation method for health-preserving vinegar powder, utilizing rice and *Lycium ruthenicum* as primary raw materials. It is prepared into *a Lycium ruthenicum* slurry, and solid-state fermentation is carried out in conjunction with multi-cultures (*saccharomycetes*, lactic acid bacteria, and acetic acid bacteria), resulting in a vinegar liquid. Then, the *Lycium ruthenicum*-astaxanthin health-preserving vinegar is prepared.	Novel food development	25/01/2019	China

- ***Cluster 2 (Average publication year 2023.5, green) "Marine biomass & biorefinery":*** The cluster encompasses articles related to the valorization of marine biomass within biorefinery and circular economy frameworks. Main keywords: microalgae, biorefineries, valorization, circular bio economy, and biofuel.
- ***Cluster 3 (Average publication year 2023.8, blue) "SSF process & optimization":*** The cluster focuses on the development and research of solid-state fermentation optimization and enzyme production. Main keywords: solid state fermentation, enzyme production, optimization, RSM and bioreactors.
- ***Cluster 4 (Average publication year 2024.3, yellow) "Marine by-products & pretreatment":*** The cluster is focused on the application of pretreatment strategies for marine by-products (e.g., crustacean) Main keywords: Shrimp shell, calcium carbonate, extraction methods, demineralization and high temperatures.
- ***Cluster 5 (Average publication year 2024.2, violet) "Bioactive compounds & biochemical transformation":*** The cluster is focused on the production of high-value bioactive compounds such as peptides, antioxidants Main keywords: amino acids, antioxidant activity and mycoprotein.
- ***Cluster 6 (Average publication year 2024.2, cyan) "Green technologies & process integration":*** The cluster is focused on the emerging technologies (e.g., ultrasound, nanotechnology) for process intensification and sustainability. Main keywords: nanotechnology, UAE, and waste valorization.
- ***Cluster 7 (Average publication year 2023.9, orange) "Biomedical & advanced applications":*** The cluster is focused development of compounds with advanced biological activity. Main keywords: Apoptosis, nanocomposites, human cell, and antineoplastic agents.
- ***Cluster 8 (Average publication year 2023, brown) "Seaweed valorization":*** The cluster encompasses studies detailing the development of research in seaweed valorization and applications. Main keywords: Macro-alga, filamentous fungus, lipids, glycerol, and anaerobic fermentation.

Additionally, a weighted mean analysis of the publication year for each cluster was performed using the number of occurrences of each keyword to highlight the development of technologies over time (Fig. 3, B). The temporal analysis showed that compared to other clusters, ***Clusters 2*** and ***8*** corresponded to more established research topics focused, primarily focused on the valorization of by-products through microbial enzymatic machinery (bioprocessing), where solid-state fermentation (SSF) emerges as a key and widely explored approach. On the other hand, Marine by-products & pretreatment (***Cluster 4***) and green technologies & process integration (***Cluster 6***) exhibited more recent average publication years (2024.3 and 2024.2, respectively), highlighting emerging trends toward the development of advanced extraction and pretreatment strategies aimed at enhancing SSF performance. These approaches include the integration of pretreatments to improve substrate accessibility, as well as the incorporation of complementary technologies (e.g., ultrasound-assisted extraction, UAE) to intensify bioprocess efficiency and maximize resource utilization.

Under the development perspectives indicated above, it is essential to consider the marine sector, as it comprises an industry that is expected to grow by 14% by 2030 (202 million metric tons) according to the report "The state of world fisheries and aquaculture 2022." (FAO, 2022). Its integration is possible through the exploration of new substrates (sea by-products), the isolation of new marine microorganisms with the capacity to perform SSF, the generation or extraction of bioactive molecules (peptides, hydrolysates, phenolic compounds, polymers, among others).

9. Emerging perspectives and future directions in solid-state fermentation research

The current field and development of knowledge in SSF encompasses its application as a method for the release and production of bioactive components for the industry. Additionally, there are some emerging and future directions that could revolutionize the current industrial scope of bioprocessing.

The application of bioactive extracts (phenolics, bioactive peptides, organic acids, among others) has been defined as components with the

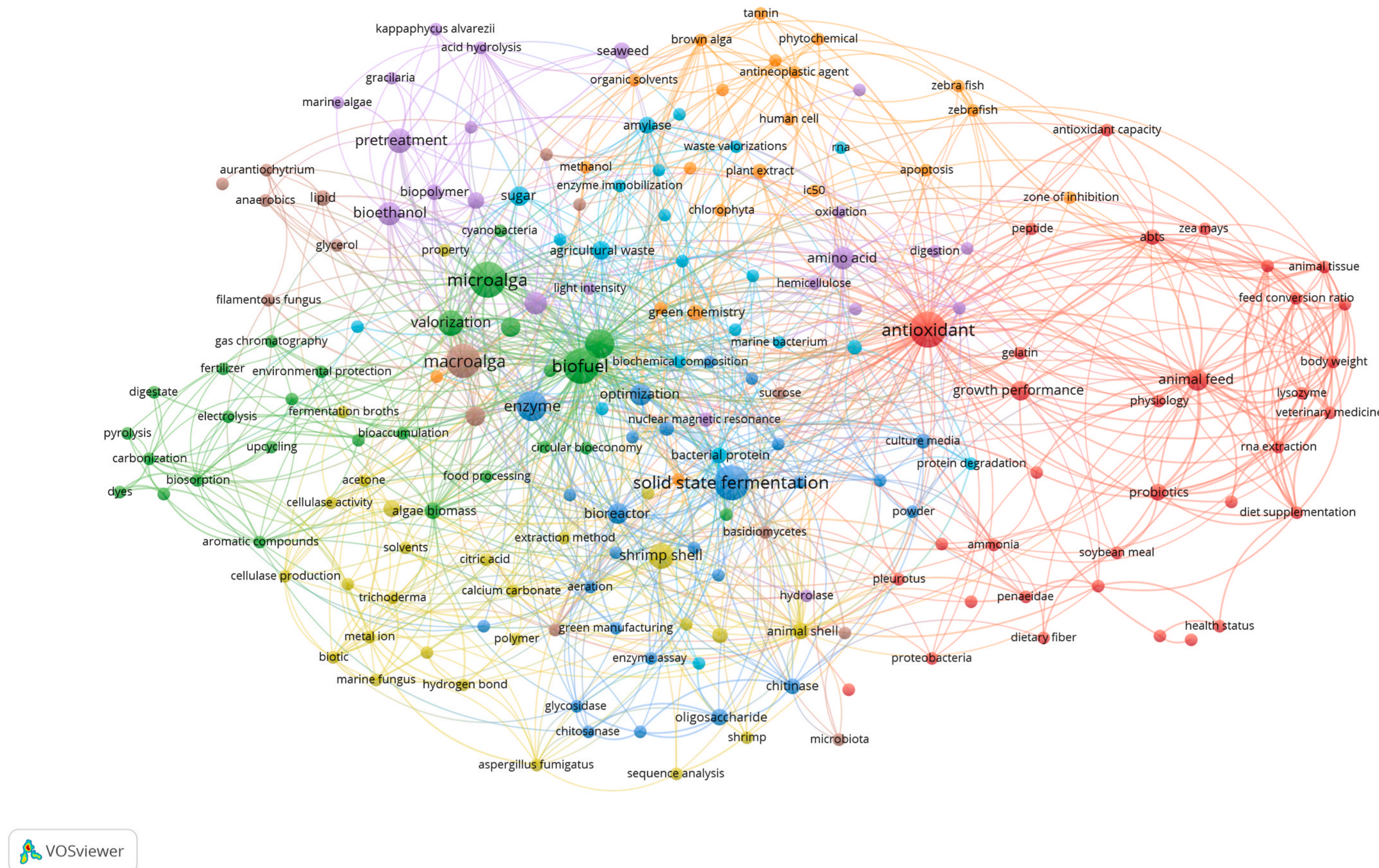

Fig. 3. Trend analysis in scientific databases by VOS-viewer into SSF technology in marine biomass between 2020 and 2026 (accessed April 08, 2026). 8 clusters: Functional applications & animal nutrition (Red), Marine biomass & biorefinery (green), SSF process & optimization (blue), Marine by-products & pretreatment (yellow), Bioactive compounds & biochemical transformation (violet), Green technologies & process integration (cyan), Biomedical & advanced applications (orange) and Seaweed valorization (brown).

ability to improve current food systems (Rivero-Pino et al., 2023). Likewise, the integration of alternative proteins (e.g., fungal proteins) represents a nutritional (high protein content) and sensory alternative that could be explored in meat analogues (Wang et al., 2023). Similarly, their integration into animal feed, or into the feeding of other protein sources (e.g., insects), has shown evidence that feeding Black soldier flies (BSF) with high-protein diets increases the total protein content of the insect (Pérez-Pacheco et al., 2022), there is precedent using fungal strains in cereals for feeding insects (Black Soldier Flies, BSF) to valorize mycotoxin-contaminated biomass or to obtain a nutritionally enriched substrate for insect feeding (higher weight) (Gulsunoglu et al., 2019; Isibika et al., 2019).

Additionally, some emerging areas in agriculture, such as the use of substrates inoculated with strains with antifungal phytopathogenic activity (e.g., *Trichoderma* spp.), as well as the development of novel materials based on mycelium-based systems recognized for their non-toxic nature, biodegradability, lightweight properties, and the possible application of by-products in their production (Saldaña-Mendoza et al., 2023).

Furthermore, the range of fungal strains and potential substrates (by-products) encompasses an attractive research area to explore (e.g., microalgae or macroalgae), with the potential to provide new green materials for industrial applications. Thus, the attractive potential of the SSF could enhance technological advancements in the industry through the patent process and lead to significant technological growth, creating new biotechnological industries.

10. Conclusion

The solid-state fermentation has emerged as an effective strategy for waste valorization within biorefinery frameworks, with predominant applications in the agri-food industry. However, its potential could be extended to sea-industry, due to the substantial volume and diversity of by-products (fish, shrimp, and algae). After revision of 458 articles (2020-2026) scientific areas for SSF applications were revealed into the value industrial chain, particularly for waste upcycling, functional applications, pretreatments, green technologies, and feed applications. Additionally, a search in intellectual property databases (Patentscope and Google patents) identified 419 patents published between 2023 and 2024, with only two patents addressing sea biomass under SSF, standing out a significant knowledge gap. This lack of evidence presents a strategic opportunity to explore SSF using marine biomass as novel substrates to produce alternative bioactive compounds that could contribute to human health and well-being as well as contribute to sustainable development.

In summary, SSF is a promising strategy for sea by-product valorization, but its industrial implementation still requires optimization. In this context: (1) Macroalgae and fishery by-products are sea by-products closest to readiness, due to composition and demonstrated fermentability; (2) Lactic acid bacteria and some fungal strains (*A. oryzae*, *R. oligosporus*, *F.venenatum*) are potential fermentative microorganism due to their safety status and strong enzymatic capabilities; and (3) the main commercialization gaps are limited scale-up, and challenging parameter control (oxygen, moisture and heat transfer) in solid systems.

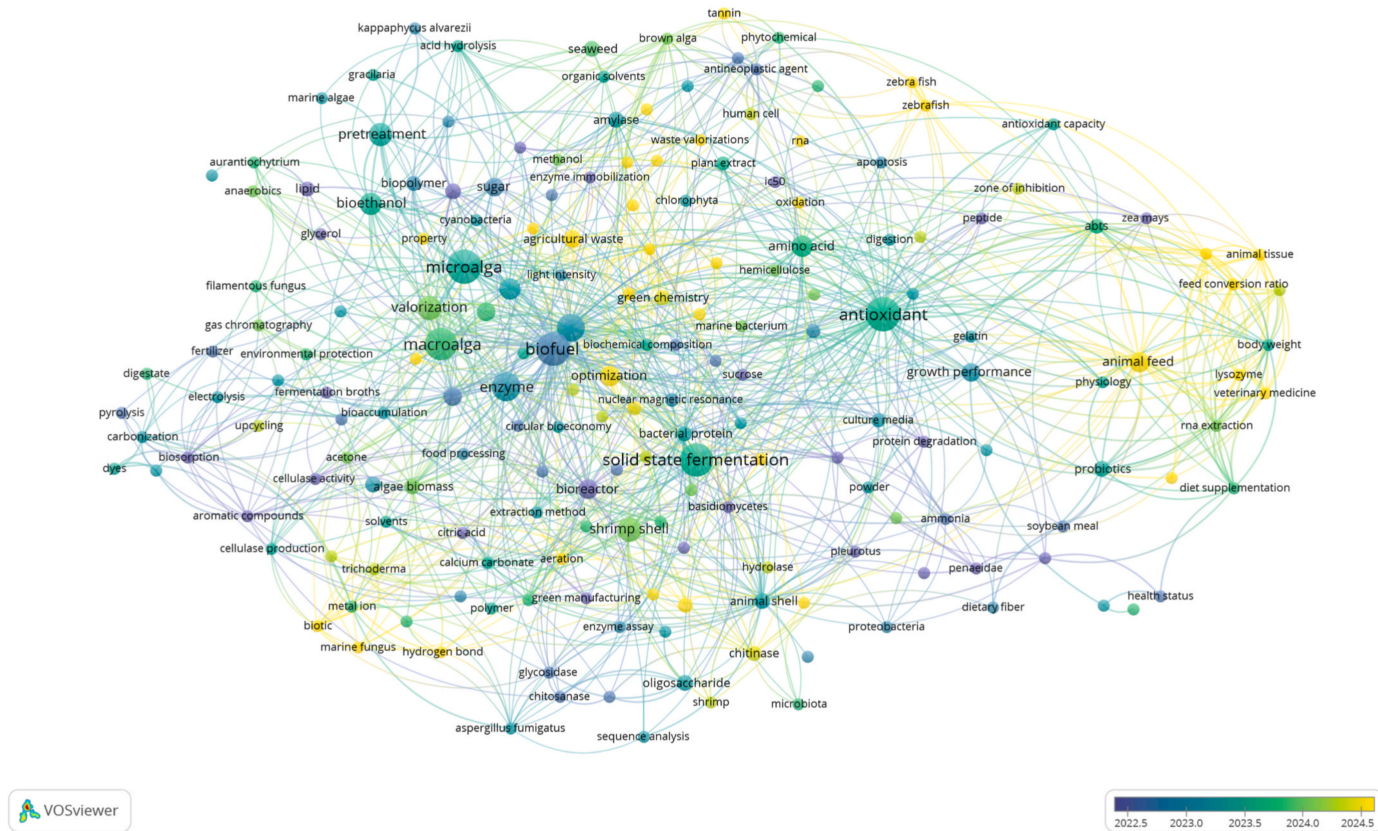

Fig. 3. (*continued*).

From an environmental science and management perspective, the implementation of SSF within sea biorefineries could substantially contribute to circular bioeconomy models by reducing the environmental impact associated with sea-industry waste disposal and underutilized biomass. The conversion of marine by-products into high-value compounds through SSF may contribute to reducing the environmental footprint associated with biomass disposal, greenhouse gas emissions, inefficient resource utilization and improve the overall efficiency of marine industrial chains. In addition, the development of SSF-based marine biorefineries may stimulate the emergence of new business models, products, and biotechnological services, potentially generating employment opportunities for technical and highly skilled professionals in the fields of biotechnology, environmental engineering, and sustainable industrial processing. Furthermore, integrating SSF as green processing technologies could decrease dependence on chemical-intensive extraction methods and promote lower energy and water consumption. Therefore, overcoming current technological and scale-up barriers is essential for industrial deployment, and for advancing sustainable environmental management, cleaner production systems, and long-term resilience in marine bioresource utilization.

Ethics statement

Not applicable.

Consent for publication

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CRediT authorship contribution statement

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Declaration of competing interest

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

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Data availability

Data will be made available on request.

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