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Review

Microbial protein-derived bioplastics from renewable substrates: pathways, challenges, and applications in a circular economy

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A B S T R A C T

Microbial protein (MP)—the protein-rich biomass derived from recovered or virgin resources—is attracting interest as a source of food and feed. However, its potential as a feedstock for protein-based bioplastics remains underexplored. Proteins offer desirable properties, including superior oxygen-barrier capabilities and complete biodegradability, making them ideal for applications from food packaging to agricultural mulches. Currently, most protein-based bioplastics derive from crops such as wheat, restricting applications and competing with food production. MP can overcome these limitations by supplying diverse proteins from various inputs, including CO_2, biomass, and liquid side-streams. In this review, we evaluate bioprocessing pathways for producing MP from renewable and waste-derived substrates from an interdisciplinary viewpoint. We also examine the technical, regulatory, market, and environmental factors to address, delineating the pathway from substrate to MP-based plastics and highlighting key challenges throughout the production chain. Novel strategies—such as efficient co-recovery of proteins with other cellular products like polyhydroxyalkanoates or direct use of microbial biomass without extraction—are essential to maximize environmental and economic sustainability. Carefully chosen processing methods for recovered proteins, including wet and dry blending or extrusion with other biopolymers, can yield diverse products. Concurrently, policy and market developments are vital for adopting MP-based bioplastics. Addressing these challenges will enable MP-based bioplastics to propel the shift toward a circular economy, diminishing dependence on fossil-derived plastics and alleviating plastic pollution.

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1. Introduction: proteins as feedstock for bioplastics

Conventional plastics have caused a global environmental crisis. More than 400 million tons of plastic waste is generated annually, of which only 9% is recycled [1]. The accumulation of non-biodegradable plastics in ecosystems poses severe ecological and health risks, particularly due to the widespread presence of microplastics in food chains and water sources [2]. In response, there is a growing demand for bioplastics—plastics derived from renewable sources that can biodegrade under common environmental conditions (e.g., at 20–28 °C and variable humidity in soil) [3]. To date, the bioplastics industry remains heavily dependent on carbohydrates (e.g., cellulose, starch, and sucrose) from plant-based feedstocks such as corn starch and sugarcane bagasse, raising concerns about sustainability and competition with food production.

Bioplastics are an umbrella term that includes a family of plastics classified based on their raw materials and end-of-life degradability [4]. They are defined as plastics that are either bio-based, biodegradable, or both [5], and can be categorized into three main groups [4] (Fig. 1):

(1) Bio-based, biodegradable plastics, such as polylactic acid (PLA),[4] polyhydroxyalkanoates (PHA), polybutylene succinate (PBS), starch, and cellulose
(2) Bio-based, non-biodegradable plastics, including bio-based polyethylene (bioPE), bio-based polyethylene terephthalate (bioPET), bio-based polypropylene (bioPP), and bio-based polyurethane (bioPU)
(3) Fossil-based, biodegradable plastics such as poly (butylene adipate-co-terephthalate) (PBAT) and polycaprolactone (PCL)

This review focuses on bio-based plastics produced from microbial biomass-derived feedstocks, which are composed partially or entirely of natural or renewable resources [5]. However, their biodegradability is not guaranteed. For instance, PHA is both bio-based and biodegradable, whereas bio-based bioPE produced from plant-derived ethylene is not.

Several approaches exist for producing bio-based plastics [6,7]. Natural polymers, such as proteins and starch, can be directly extracted from various biomass sources, including microbial biomass or biopolymer-rich waste streams, and then further modified to enhance their properties. Alternatively, bio-based monomers can be microbially produced [6] from organic substrates. After recovering the product from the fermentation broth, the monomer is polymerized. A well-known example is the sugar-based production of lactate, which is chemically polymerized into PLA. Additionally, some microorganisms are capable of producing polymers such as PHA, which can, after extraction, be directly or indirectly used as bio-based plastics. Fermentation processes can utilize a diverse range of feedstocks, including sugars, starches, oils, and agricultural residues. The choice of feedstock depends on cost and availability, and may require mechanical, chemical, or thermal pretreatment before being converted into the targeted product through microbial processes.

Protein biobased plastics have been on the market for decades, primarily relying on agricultural protein, such as wheat gluten, casein, and soy protein [8]. These sources are constrained by limited scalability, food competition, and resource-intensive processing. Recently, microbially produced proteins and protein-rich biomass have emerged as promising, scalable feedstocks for protein-based plastics. This review focuses on microbial protein (MP), the protein-rich biomass derived from prokaryotic or eukaryotic microbes. Whole-biomass, protein-based plastics have been reported from four principal microbial groups: (i) yeasts including *Saccharomyces cerevisiae* and *Kluyveromyces marxianus* [9], (ii) filamentous fungi like *Schizophyllum commune, Pleurotus ostreatus,* and *Ganoderma lucidum* [10,11], (iii) cyanobacteria including "*Spirulina*", also known as *Arthrospira* or *Limnospira*, and eukaryotic microalgae like *Chlorella* [12], as well as (iv) consortia of aerobic bacteria [13]. Interestingly, the theoretically expected end-of-life biodegradability has already been documented, including the soil degradation of biocomposite films based on *Chlorella* biomass and cellulose nanocrystals [14], as well as the anaerobic conversion to biogas of a product based on a consortium of aerobic bacteria and glycerol [15]. MP may offer several advantages over plant- or animal-derived proteins, including [16,17]:

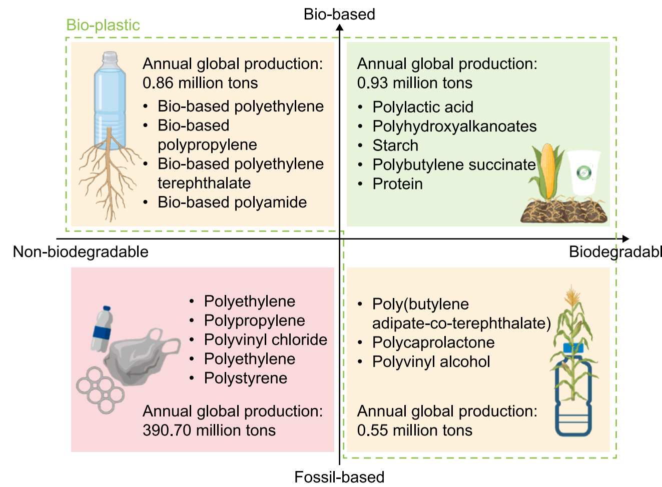

Fig. 1. Classification of plastics by raw material and end of life, with examples of plastics in each category and their annual global production [5].

- No competition with food: MP does not depend on arable land, using waste-derived carbon such as CO_2, methane, or organics in domestic or industrial wastewater.
- High protein content (Table 1): Many microbial species exhibit protein contents between 40 and 75% dry weight, surpassing those of plant-based proteins.
- Highly diverse protein profile [18] potentially yielding different properties associated with the tremendous diversity existing within the microbial realm.
- Circularity: MP production can be integrated with waste valorization and carbon capture technologies, enhancing circular economy applications.

Despite these advantages, very few studies have evaluated the potential of MP-based bioplastics. This review, therefore, aims to comprehensively bridge knowledge gaps and challenges across the entire path from substrate to plastic production. Specifically, we discuss:

(i) The bioprocessing pathways for MP production from various renewable and waste-derived substrates.
(ii) The approaches needed to make MP-based plastics.
(iii) The technical, regulatory, market, and environmental factors that must be considered to integrate MP-based plastics into the global bio-based plastics market.

[4] The biodegradability of PLA depends on the processing conditions.

Table 1
Examples of microorganisms and substrates used for microbial protein and their protein content.

Microbial species and characteristic metabolisms	Substrate	Protein content (in dry weight)	Reference
Benchmark comparison			
Fusarium venenatum (Quorn™ Mycoprotein)	Glucose	30–44%	[30]
Saccharomyces cerevisiae	Wheat, as a brewing by-product	30–40%	[31]
Chlorella vulgaris	CO_2 + carbon-rich water, light	40–55%	[32]
Bacterial protein sources			
Hydrogen-oxidizing bacteria (*Cupriavidus necator*)	$H_2 + CO_2$	50–75%	[19]
Methane-oxidizing bacteria (*Methylococcus capsulatus*)	CH_4	40–60%	[33]
Purple photoheterotrophic bacteria (*Rhodopseudomonas palustris*, *Cereibacter sphaeroides*, *Rhodospirillum rubrum*)	Short-chain fatty acids	30–66%	[34]
Purple photoautotrophic bacteria (*Rhodobacter capsulatus, Cereibacter sphaeroides, Rhodopseudomonas palustris*)	$H_2 + CO_2$	38–51%	[35]
Aerobic chemoheterotrophs (*Cupriavidus necator, Methylorubrum extorquens*)	Short-chain fatty acids	20–80%	[36]
Heterotrophs (*Methylophilus methylotrophus, Methylorubrum extorquens*)	Methanol	~70%	[37]
Heterotrophs (*Corynebacterium ammoniagenes*)	Glucose	~60%	[38]

By addressing these challenges, this review positions MP as a key enabler of novel bio-based plastics, reducing dependence on fossil resources, and mitigating plastic pollution.

2. From undervalued substrates to microbial protein

In recent years, MP has re-emerged as a more sustainable alternative to conventional agriculture for food production [17]. It should be clarified that the type of MP discussed here, also known as single-cell protein, refers to the protein-rich microbial biomass of bacteria, yeasts, filamentous fungi, and microalgae, encompassing all cellular constituents [19]. These typically are derived from a complex intracellular protein mixture produced by wild-type microbial species, in contrast to specialty extracellular proteins generated using synthetic biology tools, a process termed “precision fermentation”.

A critical factor in the sustainability of MP is the nature of the input substrate. A promising option is the use of CO, CO_2, or CO_2-derived building blocks. Indeed, CO_2 and electricity (direct or via H_2), with their seemingly high availability at single sites, can replace fossil-derived resources [20]. Since direct use of CO_2 and H_2 can be complex, a viable alternative is the immediate storage of these in stable one- or two-carbon (C1 or C2) chemicals. These C1 and C2 compounds, such as formate, methanol, methane, acetate, and ethanol, can then be used for bioproduction [21,22]. Efficient renewable electricity production could lead to a carbon-neutral process in a carbon capture-to-MP concept [21]. Given that the market for protein used in food or feed is up to 1000 times larger in volume and up to 27 times greater in value than that of potential carbon capture-derived intermediates [21], this presents both strong environmental and economic incentives. Beyond its high protein content, microbial biomass can contain beneficial components like pigments and PHA, enhancing its overall value and range of applications.

Although CO_2-derived C1 and C2 substrates are appealing, most attention has focused on the use of ‘first-generation’ virgin compounds instead of recovered substrates. Such primary virgin substrates, like glucose, are well-established in commercial products, such as Quorn™, based on the filamentous fungus *Fusarium venenatum* [23]. A major drawback of such substrates is that these processes rely on refined, food-grade inputs, resulting in high costs and competition for food uses. Other MP, such as Feedkind™, rely on natural gas, resulting in considerable greenhouse gas emissions under current production approaches [24].

To mitigate this, under certain conditions, side streams from food-grade processes can be used for MP production, as they supply not only carbon but also macronutrients such as nitrogen, phosphorus, and sulfur, as well as the required micronutrients. For example, potato wastewater has been extensively explored [25] since the 1980s [26], while whey has been considered a substrate since the 1970s [27]. Lower-value resources, such as agricultural and domestic wastewater, also exist. While these substrates come at a “negative cost” today, requiring investments to properly treat them, there are evident concerns about the impact of pathogens, trace contaminants (e.g., heavy metals) on the final product. Moreover, guaranteeing a stable product based on such streams that alter over the year makes market uptake challenging. To address these challenges, several alternative routes have been explored. Depending on the side-stream quality, organics can be directly valorized if they meet food-grade requirements [25,27] or converted into simpler, more stable intermediates such as lactic acid [28]. If the substrate is not food-grade, approaches such as pyrolysis can be applied to produce energy-rich gaseous substrates such as syngas. Another route involves methanotrophs, where waste organics are first converted to biogas, which separates from most water-borne contaminants. Both the methane and the carbon dioxide in the biogas can then be converted to MP, provided a reductant such as hydrogen gas is also available [29].

In summary, a wide range of yeasts, fungi, microalgae, and bacteria can be utilized for MP production (Table 1), with all these organisms capable of dark production (not requiring light). Additionally, phototrophs, such as microalgae and purple phototrophic bacteria (PPB), can utilize light as an energy source and CO_2 as a source of carbon. PPB, in particular, are metabolically versatile and have high biomass yield. On average, filamentous fungi contain 20–50% protein, yeasts about 30–40%, microalgae 30–60%, and bacteria have the highest protein content at 40–70% (Table 1). Numerous examples of MP derived from various microbial species and substrates exist, with some already available on the market and others still in the development phase.

3. Challenges in current microbial protein applications for food or feed

The full deployment of MP currently faces not only technological and economic challenges, but it also needs to address consumer acceptance and navigate increasingly stringent food regulations [39]. Technically, the high nucleic acid content of microbial biomass, particularly RNA, poses a nutritional issue as excessive intake, particularly of purines, can lead to increased uric acid levels, risking adverse health effects such as gout, kidney stones, metabolic syndrome, and cardiovascular diseases. This issue can be partially mitigated through processing methods, such as applying a heat shock or performing protein isolation [40]. From a consumer acceptance perspective, the odor and texture derived from microbial biomass may not appeal to the human palate. Effective preparation, cultural considerations, education, and marketing are essential to overcome unfamiliarity and a lack of consumption experience [41]. Importantly, although food applications currently dominate research on MP, they are challenging to commercialize. Consumer perception and acceptance play a crucial role here, as acceptance is shaped by factors such as food neophobia [42], perceived naturalness, healthiness, and environmental sustainability [39,43]. Even when environmental and nutritional benefits are recognized, limited awareness and negative associations can hinder uptake, while unanswered questions around taste and texture may add further barriers [43]. Material applications (e.g., plastics) may face less consumer resistance and thus achieve faster adoption [39], although similar societal concerns could still emerge. This highlights that in the case of food, regulatory approval alone will not guarantee success; public trust and acceptance must be actively promoted through targeted communication strategies.

Regulatory hurdles remain another significant barrier to deploying MP to the market, particularly in the European Union (EU), where novel foods require comprehensive technical dossiers and adherence to Regulation (EU) 2015/2283, as well as the submission of detailed technical dossiers encompassing compositional, toxicological, and exposure data. The European Food Safety Authority (EFSA) can take up to 24 months to give a determination on the risk assessment dossier [44]. As a result, bringing MP to the market as food or feed is challenging, leading to slow uptake and limited availability of products today. While EFSA approvals have been granted for selected microbial products (e.g., *Yarrowia lipolytica* biomass, milk oligosaccharides from *Corynebacterium glutamicum*), approvals for bacterial biomass remain rare due to limited historical consumption and data gaps. The main challenges are therefore not regulatory impossibility but the high cost, extensive data requirements, and lengthy, iterative EFSA review process. By contrast, MP-based plastics not intended for ingestion fall outside the scope of Novel Food legislation and are subject to lighter requirements (e.g., migration testing, following the EU regulations on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and on the Classification, Labelling and Packaging of substances and mixtures (CLP)), making staged deployment from non-food to food-contact applications a practical strategy for gradually introducing microbial ingredients.

4. Using protein as bio-based plastics

4.1. The roots of protein-based plastics

While proteins play an indispensable role in human nutrition, they have also been utilized for non-food purposes for over a century. The first documented protein-based synthetic polymer was developed in 1897, preceding synthetic plastics like Bakelite, which emerged in 1930. The so-called “galalith” or “milkstone” was made by crosslinking the amino groups in casein (milk protein) using formaldehyde. The resulting thermoset was used to craft jewelry and decorative items. Protein-based plastics have been predominantly used for food packaging since the 1950s, whereas natural protein-containing products for food preservation have been utilized for centuries. To understand why proteins are attractive for high-value applications, such as food packaging, it is essential to first understand what they should contribute.

4.2. Proteins for food packaging

Today, most research and development efforts on protein bioplastics focus on their use in food packaging [45], with the protein derived mostly from plants (e.g., soy, zein, gluten) and animals (e.g., whey, casein, collagen) [46]. Food packaging is a significant contributor to plastic consumption, and innovations aimed at developing more sustainable, bio-based plastics in this sector hold substantial potential for contributing to environmental sustainability [47]. Effective food packaging is essential for maintaining the quality and safety of the contents. Depending on the food, packaging may need to provide an excellent barrier against oxygen, moisture, oils, fats, and acids, which is where protein plastics hold unique properties. In other cases, the packaging should be permeable to excess moisture or allow oxygen to penetrate, which helps preserve the quality of fresh fruits and vegetables. Protein-based food packaging has found applications as films, bags, bottles, and trays [46]. Regardless of the specific use, the packaging must be easy to seal well. Additionally, food packaging plastics must comply with food contact legislation (e.g., EU 1935/2004) and packaging waste legislation (e.g., 94/62/EC). The European legislation regarding the latter is currently undergoing major revision, with new regulations emphasizing re-use, reduction, and recycling. The upcoming Packaging and Packaging Waste Regulation is expected to promote the use of compostable plastics for packaging fruits and vegetables, as well as permeable bags for tea, coffee, and other beverages. Looking ahead, there will likely be a focus on incorporating more recycled and bio-based content in food and other packaging materials, where protein-based feedstocks of microbial origin could play a substantial role. Compared to conventional plant- or animal-derived proteins, microbial materials offer distinct advantages: they can be synthesized without relying on agricultural or fossil resources, degrade faster than many synthetic biodegradable plastics and most plant-derived bioplastics [15], and can provide antimicrobial functionality [48] and excellent barrier properties [49]. These features are particularly relevant for applications such as oxygen-sensitive food packaging, compostable films, and antimicrobial food-contact materials.

4.3. From protein chemistry to functional bio-based plastics

Proteins are natural heteropolymers that can form supramolecular networks by physicochemical (non-covalent) interactions, and—to a lesser extent—by covalent bonding. The amino acids, the building blocks of proteins, define the type and strength of the interactions and determine the properties of the protein-based plastics (Table 2) and the resulting networks. Plastics have been produced using proteins isolated from various plant sources, such as corn zein, wheat gluten, soy, nuts, and seeds, as well as animal sources, including milk, eggs, gelatin, collagen, and keratin [53].

The structure of the protein significantly influences the properties of the derived plastic, including the glass transition temperature, crystallinity, and elastic modulus [50]. High-molecular-weight proteins (>200 kDa), such as glutenin, and fibrous proteins, like collagen, can often be used to form films with good mechanical properties. In contrast, (pseudo)globular proteins, such as glycinin and casein, typically require unfolding to form a network structure. The secondary structures of proteins play a crucial role in determining the properties of protein-based thermoplastics and the process by which they can be converted into plastics. Many proteins tend to form α-helices, β-sheets, and other (crystalline) structures that naturally stabilize the proteins. These are important points to consider when using MP as feedstock for bio-based plastic production, as microbial cells contain hundreds of proteins with molecular weights ranging from 10 to 150 kDa [51], the (relative) abundance of which also varies depending on the cultivation conditions [18].

Table 2
Comparison of the main properties of biopolymers [53] and PLA [54].

Polymer	Proteins[a]	Polyhydroxyalkanoates	Polylactic acid
Monomers	Amino acids	Hydroxyalkanoates	Lactic acid
Biocompatibility	Excellent	Excellent	Good
Elastic modulus	<2 GPa	0.5–3 GPa	2–4 GPa
Tensile strength	<40 MPa	15–40 MPa	20–60 MPa
Elongation at yield	<10%	4–8%	2–6%
Elongation at break	<200%	<200%	<100%
Brittleness	Brittle	Ductile	Ductile
Glass transition	<80 °C	−15–5 °C	45–60 °C
Melting point	120–140 °C	168–182 °C	150–162 °C
Gas barrier	Water barrier	Oxygen barrier	Relatively poor
Water resistance	Hydrophobic	Hydrophobic	Hydrophilic
Thermal resistance	Relatively low	Intermediate	Relatively high
Ultraviolet resistance	Good	Intermediate	Poor
Uses	Cast film Extruded sheets Compression molding Injection molding	Adhesives Fibers Packaging Biomedicine	Biomedicine Packaging Textiles 3D printing
Degradability	Enzymatic in water, soil, and during industrial composting	Enzymatic in water, soil, and during industrial composting	Limited biodegradation, hydrolytic at elevated temperatures during industrial composting

[a] The properties of protein-based plastics depend strongly on the structure of the protein and the plastic composition [55,56]. Therefore, the given ranges are much wider than for PHA and PLA.

These physicochemical interactions and physical crosslinks must be broken using an agent, such as heat or a solvent, to process the proteins and transform them into plastics with the desired properties. During processing, the polymer chains rearrange into a three-dimensional network, which is again stabilized by (new) interactions once the agent is removed. This can be achieved through wet processes such as dispersion or solubilization, or dry processes, based on the thermoplastic properties of proteins under low-water conditions (<10 wt%) [52].

Wet processing of proteins utilizes a solvent, typically water, to disrupt the physicochemical interactions and physical crosslinks. The dissolution of protein can be improved by the addition of a denaturant, such as strong acids or bases, to further disrupt the folded structure. Dissolution is further improved by increasing the temperature above relevant transition temperatures, such as the glass transition temperature, melting temperature, or denaturation temperature, and by increasing the overall solubility of the protein in the used solvent. The protein solution is then cast as a coating, a film, or in a mold, and the protein-based plastic product is obtained after the solvent is removed. Dry processing methods do not use solvents; however, they may still employ small amounts of water (up to 10 wt%) or other denaturants to lower the denaturation temperature. Thermal processing of proteins is performed above the relevant transition temperatures of the proteins, and under high shear conditions [57]. The processing temperature should be above the glass transition temperature of the amorphous fraction, above the melting temperature of the crystalline fraction, and above the denaturation temperature [58]. These temperatures depend on the chemical structure of the protein and can be lowered by the presence of plasticizers and denaturants. This is crucial to prevent any undesired degradation of the protein's chemical structure. The most common dry processing method used for processing proteins and producing protein-based plastics is extrusion [50], complemented by molding techniques such as injection molding and compression molding. Molding techniques are usually performed after the protein-based plastics have already been compounded using extrusion-based techniques. The final protein-based product is obtained after cooling and solidification, during which physicochemical interactions are re-established, and crystallization and other structure-forming processes occur. Extrusion and compounding of certain plant and animal proteins have been well established in food science, both for bio-based plastics and other applications. For example, the thermoplastic and chemical behavior of wheat gluten under extrusion has been studied [59]. Extrusion conditions—such as temperature, screw speed, moisture content, presence of plasticizers, and shear forces—strongly influence the chemical structure and physical properties of protein-based extrudates [60].

Additional agents, such as plasticizers, can be introduced during solubilization or extrusion to increase the mobility of the protein chains by decreasing the number of interactions between them, thus preventing the formation of secondary structures and increasing the free volume. At the same time, plasticizers still provide ample sites for new interactions with the unfolded/denatured proteins (Fig. 2). Glycerol is the most commonly and successfully used plasticizer for bio-based plastics [61]. Other natural plasticizers include other natural polyols, fatty acids, and oils. Proteins can also be combined or blended with other (bio)-polymers, such as cellulose, starch, or PLA, to benefit from the complementary properties of either of the components [62]. Proteins generally offer excellent barrier properties against oxygen and biodegradability, while other biopolymers provide enhanced mechanical and thermal properties, as well as improved rheological behavior, which is required for thermoplastic processing. A recent study reported the effect of (waste) nanoplastics on the secondary structure of proteins [63]. Similarly, polymers and additives that are blended with proteins also affect the potential formation of secondary structures.

4.4. Turning polymers into attractive plastics and beyond

As previously discussed, protein-based bioplastics exhibit unique functional properties, including excellent oxygen barrier properties and full biodegradability (Table 2). However, they often fall short in mechanical strength and processability compared to synthetic polymers. This limitation explains the widespread use of multilayered food packaging, as no single material currently meets all functional requirements. Exploration of novel protein sources, control over the protein composition during (microbial) synthesis [18,64], and advances in biohybrid systems, such as blends and composites, can expand the applicability beyond multilayer applications [62]. These innovations may enable broader

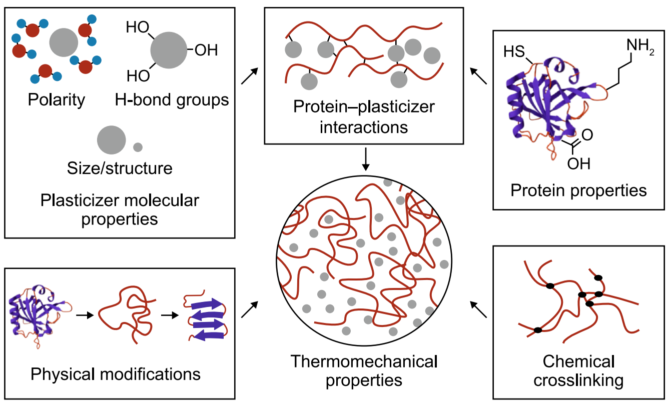

Fig. 2. Protein-based plastics will have properties that depend on many factors, from physical to chemical modification to the initial composition. Adapted from Ref. [67], licensed under the Creative Commons Attribution 4.0 International License (CC BY 4.0).

manufacturing compatibility and help unlock the full sustainability potential of these biopolymers. The diversity of microbial feedstocks further enhances the potential to achieve different plastics, while genetic and chemical modifications offer control over protein structure and the properties of the derived material [65]. Proteins can further be irreversibly crosslinked chemically into stable polymer networks (Fig. 2) using common crosslinking strategies, such as epoxidation, for inter- or intramolecular crosslinking [66]. These irreversibly crosslinked protein-based networks offer superior mechanical properties and thermal, chemical, and solvent resistance, while sacrificing their reprocessibility and, in many cases, also their biodegradability. Nevertheless, as MP can be derived from CO_2, it may mean long-term CO_2 storage.

Protein-based bioplastics derived from sources such as albumin, soy, and whey have also demonstrated antibacterial properties [56], adding valuable functionality, particularly in food packaging and medical applications. The albumin–glycerol and whey–glycerol protein-based plastics showed the strongest antibacterial properties. Albumin exhibits antimicrobial activity through lysozyme, an enzyme that lyses bacterial cells, whereas whey contains immunoglobulins and glycomacropeptides that can bind toxins and inhibit bacterial infection. Additional antibacterial effects may arise from additives that possess antimicrobial properties themselves. Notably, bio-based plastics plasticized with glycerol showed better antibacterial performance compared to those using water or natural rubber latex [56].

5. Microbes are almost fully polymer blends

Microbial biomass is mainly composed of protein, nucleic acids (RNA and DNA), and potential storage molecules such as PHA or glycogen. All of these are, in fact, polymers, even DNA, and thus upon fractionation multiple products can be obtained [68].

5.1. From microbial biomass to extracted protein

Once microbial cells have been harvested from the fermentation broth via centrifugation or filtration, the cell material can be further processed for more refined bio-based plastic applications. One such option is to extract the protein from the biomass [69–72].

Cell disruption methods include mechanical disruption, chemical extraction, and enzymatic hydrolysis, which are often combined to maximize the yield. Mechanical disruption aims to efficiently break down microbial cell walls and release intracellular proteins without the extensive use of chemicals [73]. High-pressure homogenization, for example, subjects microbial cells to pressures up to 150 MPa, causing cell rupture and protein release [73]. Ultrasonication utilizes high-frequency sound waves to achieve a similar effect [74], whereas bead milling employs grinding media to mechanically disrupt cells [75]. These techniques are favored for their scalability but can generate heat, which may denature proteins if not properly controlled. Chemical methods typically employ solvents or alkali to solubilize proteins, whereas enzymatic hydrolysis utilizes specific enzymes under mild conditions to break down cell walls and release proteins [76,77]. Although enzymatic hydrolysis is gentler and preserves protein structure, it may be slower and more costly. A key consideration regarding extraction methods is that they inherently influence the properties of the final product—an aspect that is often overlooked.

In most cases, an additional step is needed to separate the proteins, which are part soluble and part insoluble, from the rest of the biomass, which consists of membrane fragments, nucleic acids, and other components that may be undesirable in the final product. Cell debris can be separated from the water-soluble proteins and other soluble compounds in the supernatant by centrifugation, which evidently implies that most membrane-associated proteins will be lost [78]. The methods of choice for further purification depend on the protein(s) of interest, desired purity level, and downstream applications. Through ultrafiltration or microfiltration, proteins and polysaccharides in the supernatant can be partially purified and concentrated, for instance. Separation of proteins from other cellular components commonly occurs via precipitation using ammonium sulfate or organic solvents. Subsequent purification may involve chromatography techniques, such as ion exchange, size exclusion, or affinity chromatography, which further purify proteins based on charge, size, or specific binding affinities [79,80]. When aiming to produce standard protein-based packaging materials, it becomes evident that most existing methods are difficult to justify in terms of cost and environmental sustainability.

5.2. Utilizing all microbial polymers beyond proteins

As highlighted, microbial cells contain biopolymers other than proteins. For example, they can store PHA, even at levels up to 80% [81]. This accumulation typically occurs under conditions where the carbon substrate is abundant, but growth is impaired by limited nutrient availability (e.g., nitrogen). Depending upon the type of microbes and carbon substrate used, a range of PHA can be produced and are usually classified based on the number of carbon atoms in their monomers. Due to its high biodegradability and comparable properties to some traditional fossil-based plastics, such as polyethylene and polypropylene, PHA production has received increasing attention [82]. However, current production processes are geared towards producing only one product, and the processing of PHA-rich biomass typically involves a high-temperature and/or low-pH treatment, which destroys all protein.

Despite its advantages and being a high-value commodity polymer, the commercialization of PHA has been limited due to its high production cost ($1.50–5.00 kg^{-1}, compared to $0.25–0.50 kg^{-1} for fossil-based PP) [83], primarily driven by upstream and downstream costs. In the case of co-production and co-valorization of MP and PHA, the processing cost can be shared between the products (Table 2) while maximizing carbon and nutrient recovery. So far, although co-valorization can be achieved without extraction and/or separation, it has only been studied in a limited number of cases. Pesante and Frison reviewed approaches for the valorization of PHA-rich biomass beyond PHA recovery for bio-based plastics. They identified the direct extrusion of PHA-rich biomass as an emerging method to produce biocomposites, thereby eliminating the need for PHA extraction. This approach appeared feasible if the biomass contained at least 50% PHA, with protein also being part of the product [84]. Additionally, promising results were observed for *Cupriavidus necator* biomass containing polyhydroxybutyrate (PHB) and proteins, which could be converted into thermoplastic composites without requiring purification steps [85].

If both proteins and PHA are desired as separate enriched fractions, biomass processing could involve several steps (Fig. 3): (1) cell disruption, resulting in a mixture containing cell debris, PHA granules, and soluble proteins; (2) (water-based) extraction to recover the majority of (water-soluble) proteins, and (3) solvent-based extraction to isolate the PHA from the remaining pellet. Both fractions can be further purified, if necessary, and dried, for example, by lyophilization or spray drying, to obtain stable powders. In such an approach, Bastianelli et al. [86] combined the production of PHA for the bio-based plastics market with the generation of protein hydrolysates as biostimulants for the agricultural sector. After hydrolysis of PHA-enriched biomass, PHA was separated from the protein hydrolysates by centrifugation. The challenge was to find the right balance between releasing enough proteins/peptides and maximizing the recovery of intact, high-quality PHA.

6. Synergies between microbial protein and other microbial polymers

Microbial biomass composition includes up to 80% protein, around 10% lipids, 10% carbohydrates, up to 20% nucleic acids, and about 10% minerals, depending on the specific biomass [19]. As discussed in Section 5.2, depending on the conditions, the cells can accumulate PHA – even up to 80% on a dry weight basis [81]. We have discussed processes targeting either protein or PHA production, occasionally using whole microbial biomass. The production of either protein or PHA is conducted at dedicated biomass-receiving plants, which limits the production size relative to conventional approaches for large-scale polymer production. Extraction methods are typically not designed to recover both constituents; thus, must be carefully tailored and combined to avoid compromising, or even destroying, the other cell constituents [84,87,88].

The crux of approaching microbial biomass as a whole (Fig. 4)—containing all polymers, e.g., protein and PHA – is that potentially the efficiency of real-life resources is better, and overall production quantities can be increased. An earlier study [85] also demonstrated that whole biomass, containing both proteins and PHA, can produce a biocomposite with better properties than individually extracted PHA, while also avoiding extensive purification costs.

To demonstrate better resource utilization efficiency, we will use the example of potato processing wastewater. We scale here at some 5000 m^3 per day and a composition as described earlier (6.5 kg COD m^{-3}, 0.22 kg total ammonia nitrogen (TAN) m^{-3}) [89] (see assumptions and calculations in Supplementary Materials). Assuming that 50% of COD is carbon, the wastewater has a C-to-N ratio of 14, which is on the low end for achieving good MP production [90], but too high to enable a high PHA content. To produce protein, supplementation of at least 0.14 kg TAN m^{-3} would be required. Conversely, using this wastewater directly to produce PHA would result in 80% of the organic substrate being allocated to conventional cell growth due to the presence of nitrogen (assumed as a limiting nutrient), leaving only about 20% of the organics for PHA synthesis. Achieving truly PHA-rich biomass (80% PHA) would require an additional 25 tons of organics, such as organic acids or sugars (molasses), beyond the incoming 32 tons. Focusing solely on either protein or PHA production requires substantial adjustments to the input streams.

If the wastewater remains unmodified, the resulting biomass will contain about 40% protein and 40% PHA. Depending on the purification needs, at least 80% of the cell mass can be harvested as useful products, yielding about 8 tons of protein and 8 tons of PHA from 32 tons of organic substrate. This represents a considerable carbon efficiency improvement over the scenarios discussed before, while also eliminating the need for external inputs. It is too premature to quantify the economic and environmental benefits, but the assumption that higher carbon uptake efficiency reduces waste generation and associated impacts, such as CO_2 emissions, is not egregious. Avoiding the need to import nitrogen or organic substrates (e.g., acetic acid) or nitrogen offers logistical and cost advantages, provided the resulting product values are not lower than those from single-production approaches. We summarize

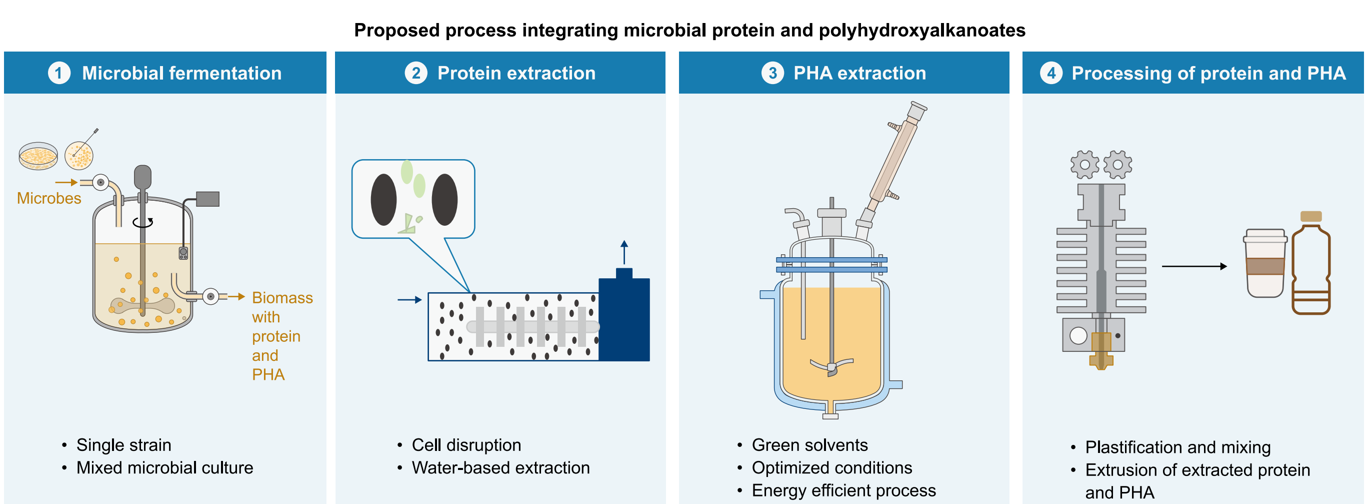

Fig. 3. Schematic representation of the proposed process integrating the valorization of microbial protein and polyhydroxyalkanoates (PHA) as biodegradable bio-based plastics.

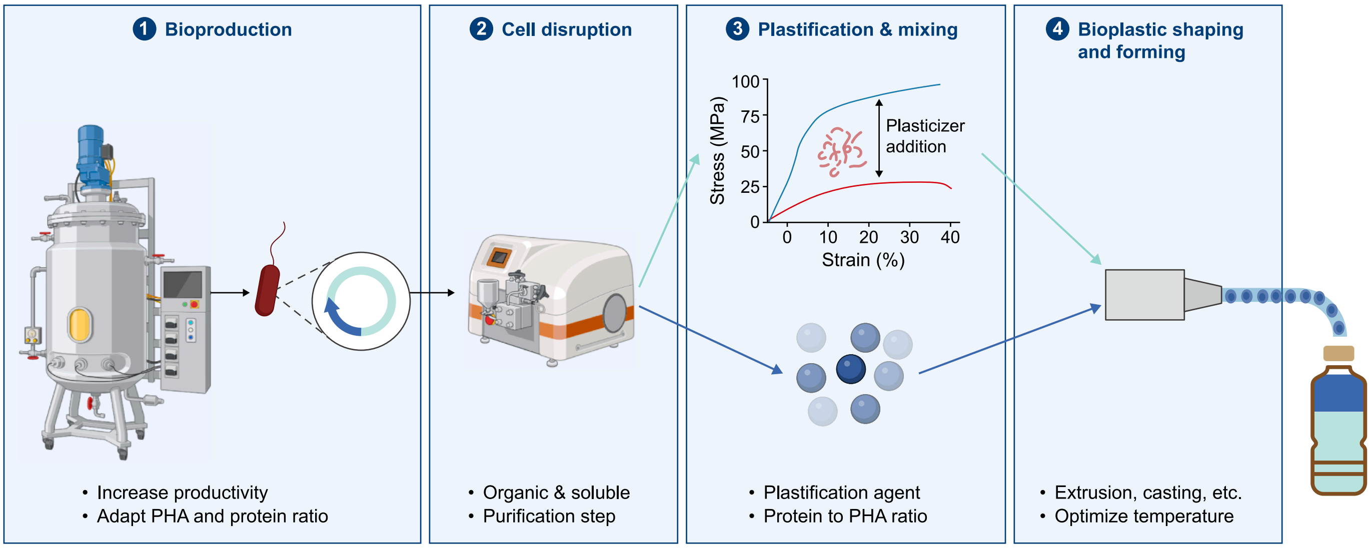

Fig. 4. Schematic representation of the proposed process integrating microbial protein (MP) and polyhydroxyalkanoates (PHA). The process includes: (1) Bioproduction: optimization of microbial biomass productivity and tailored PHA and protein ratios. (2) Cell disruption (optional step): extraction of intracellular components through mechanical methods, yielding soluble and organic phases and possible purification steps. (3) Plasticization and mixing: incorporation of plasticization agents (e.g., glycerol) and adjustment of protein-to-PHA ratios to enhance thermochemical properties based on desired products. (4) Bioplastic shaping relies on thermal and mechanical methods to form materials for specific uses. Extrusion produces continuous profiles under controlled shear and heat. Injection molding enables the production of precise, complex parts, while compression molding forms dense shapes through the application of pressure. Casting allows for the creation of simple or customized forms from liquid biopolymers. The elements of the figure are created using BioRender.com.

Table 3
Some of the key challenges and opportunities for the generation of microbial biomass-based bioplastics.

Process step	Challenge	Opportunity/solution
Bioproduction	Use of mixed cultures leads to the presence of impurities, and may be difficult to commercialize	Cost-benefits of avoiding sterilization might counteract the potential need for processing steps. Seek applications not requiring high purity
	High costs of pure culture production and difficulty in maintaining axenicity	Higher quality products, e.g., for food packaging
	Microbial biomass is composed of multiple components and may not yield the required functional properties [13]	Other components may also positively contribute to this application, such as nutrients in agricultural plastics. Lower cost for whole biomass use
Extraction	No extraction protocols exist for simultaneous protein and PHA recovery	Simultaneous recovery may not be required as long as the complexity of downstream processing can be reduced. Higher carbon usage and the omission of substrate modification can offset the complexity of extraction. The required purification degree of fractions is not yet known, and partial enrichment is expected to be sufficient for certain applications
	Maintain different biopolymers intact or with the desired properties for the target applications	Develop novel extraction approaches that reduce stress on other polymers (than the main target) [84]; Keep temperatures below the denaturation temperature. Avoid the use of hydrolyzing chemicals
	There is still waste: Nucleic acids will be amongst the largest fractions of the “leftover” cellular constituents	It has been shown that nucleic acid (specifically DNA-based) plastics are possible [68,92]
Plastic formulation	Potential variations in protein and PHA composition and relative ratios between both may lead to variability in the final product's properties, making standardization difficult	The variability—provided it stems from microbial species/strain and input combinations rather than process instability—can be a key asset for supporting a wide range of applications
Getting microbial protein-based plastics to the market	The sustainability of MP needs to be clearly demonstrated, which is complicated by the wide variety of input and usage options	In the context of MP for feed or food, several have demonstrated clear environmental benefits. MP for plastics could build on this foundation
	Regulatory barriers exist towards the use of plastics	The regulatory requirements for food are considerably different than those for agricultural packaging or foils, and applications need to be staged with development
	Market development may be challenging, as MP is unknown, pricing for fossil analogues is low, and volumes may be low in the foreseeable future	Niche markets exist where biodegradable plastics containing nutrients can be of added value, and low value packaging bringing sustainability can attract end users

with some considerations:

(1) Side-streams and wastewaters vary in composition and, depending on the target product, may be more suitable for PHA or for protein production. In rare cases, the composition is ideal for one specific target, though
(2) Producing microbial biomass without additional supplementation eliminates the need for external fossil-derived inputs, as all nutrients originate from the substrate itself.

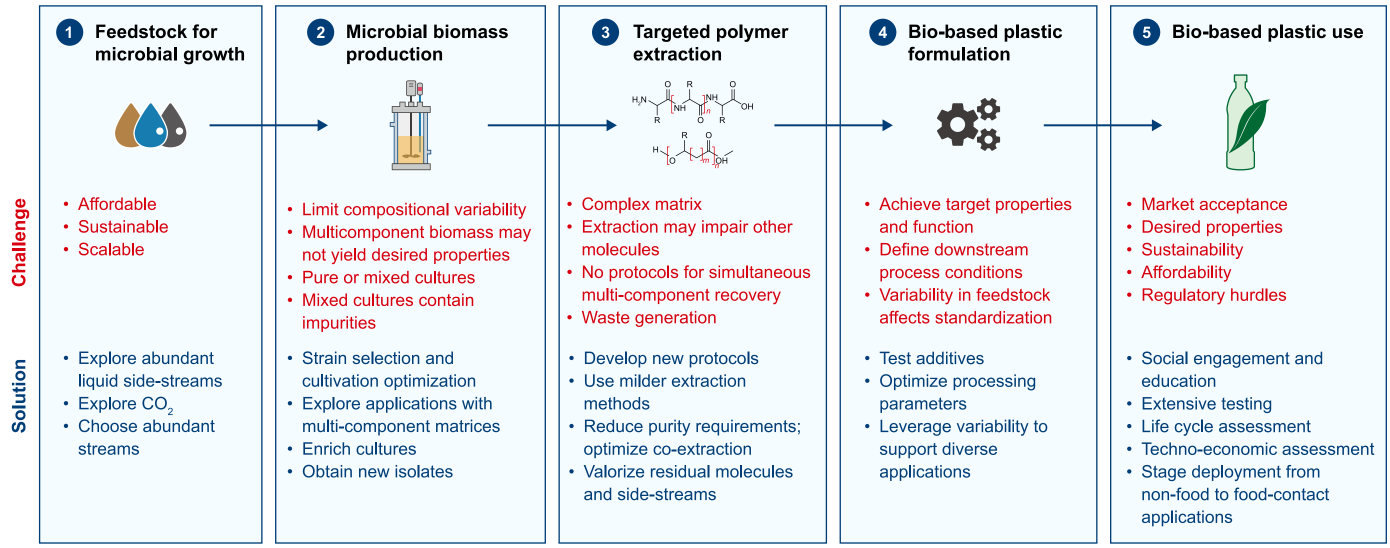

Fig. 5. Proposed roadmap for future research, highlighting key challenges and potential solutions across the main process steps.

This aligns with the key approach in organic certification [91]. Approval ultimately depends on meeting region-specific regulatory standards, obviously

(3) Integrated microbial biomass production can yield more than 80% useful product, surpassing the current limits of up to 65% for protein and up to 80% for PHA, while efficiently utilizing both organic matter and nitrogen

The above section again highlights the major importance of developing appropriate fractionation methods that do not focus on a singular product.

7. Bringing microbial protein-based bioplastics into reality

As with any new interdisciplinary production approach, clear challenges and trade-offs exist. Table 3 provides a non-exhaustive overview of the key challenges and opportunities associated with the value chain of converting microbial biomass into plastics. A proposed roadmap for future research, highlighting the main challenges and potential solutions at each step of the process, is outlined at each process step (Fig. 5). While the path to microbial biomass-based bioplastics contains challenges, it also presents significant opportunities for innovation. The unique properties of microbial biomass can lead to the development of versatile products that meet diverse market needs and the growing demand for sustainable materials.

8. Conclusions and way forward

Microbial protein represents a promising feedstock for the production of bio-based plastics, utilizing both virgin materials and side streams, and leveraging the metabolic potential of microorganisms. Proteins from microbial biomass offer excellent barrier properties for bio-based plastics; however, challenges remain in improving their mechanical properties and developing more efficient processing techniques. Combining proteins with other biopolymers or utilizing whole microbial biomass can enhance the functionality and sustainability of bio-based plastics. To realize the potential of MP-based bioplastics, it is first essential to determine whether cell disruption or the extraction of specific intracellular components is necessary. If so, extraction protocols should be optimized to enable the efficient co-extraction of target compounds. Emerging strategies—such as ultrasound-, microwave-, or pulse-electric-field-assisted extraction—could improve efficiency and reduce environmental impacts, though further optimization and safety validation are required. Digital tools, including artificial intelligence, may also support the design of more resource-efficient downstream schemes tailored to bioplastics. Creating methods that allow for the efficient recovery of both protein and other valuable biopolymers, such as PHA, will improve overall resource utilization efficiency. This begins with optimizing cultivation processes that balance the cost-effectiveness and high-quality product outputs, using co-production strategies with either mixed- or pure-culture biotechnology.

Producing a plastic is not sufficient to get it to the market. Policy and market development play a critical role in the successful deployment of microbial biomass-based bioplastics. Engaging with regulatory bodies to streamline approval processes and promoting the benefits of microbial biomass-based bioplastics to niche markets, particularly those that value environmental sustainability, will facilitate their adoption. Highlighting the environmental advantages and exploring niche markets can attract end users and drive market acceptance. By addressing these issues, the pathway to sustainable, high-performance bio-based plastics can be facilitated, allowing for MP to become a mainstream solution for reducing plastic pollution and enhancing environmental sustainability.

CRediT authorship contribution statement

Myrsini Sakarika: Writing - Review & Editing, Writing - Original Draft, Project Administration. **Joost Brancart:** Writing - Review & Editing, Writing - Original Draft, Funding Acquisition. **Shreyash Anil Gujar:** Writing - Original Draft, Visualization. **Steven De Meester:** Writing - Review & Editing, Funding Acquisition. **Luis Diaz Allegue:** Writing - Review & Editing, Visualization. **Leen Bastiaens:** Writing - Review & Editing, Writing - Original Draft. **Peter Ragaert:** Writing - Review & Editing, Writing - Original Draft. **Siegfried E. Vlaeminck:** Writing - Review & Editing, Funding Acquisition. **Heleen De Wever:** Writing - Review & Editing, Writing - Original Draft. **Korneel Rabaey:** Writing - Review & Editing, Writing - Original Draft, Project Administration, Funding Acquisition.

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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Appendix A. Supplementary data

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