

Microalgal starch as a precursor material for bioplastics: A critical review of structural and functional characteristics

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Abstract. Microalgal starch has emerged as a promising alternative to terrestrial starches for bioplastic production. This is due to its distinct physicochemical characteristics and sustainable cultivation requirements. Microalgal strains consistently show very small granule sizes, lower crystallinity, longer amylopectin chains, and species-dependent thermal and rheological behavior. These traits influence gelatinization, plasticizer interaction, and melt formation. They also support efficient processing and enable thermoplastic starches with higher elasticity and toughness. Mechanical strength remains lower than crop-derived thermoplastic starch (TPS). However, recent studies show that blending with additives such as chitosan can improve film strength and stability. This indicates clear potential for composite development. Despite these advantages, several challenges persist, including high-energy cell disruption, variability in starch purity, and limited techno-economic evaluation. This review synthesizes current knowledge on the physicochemical properties of microalgal starch and examines their implications for bioplastic performance. It also highlights key research gaps that must be addressed to advance microalgal-based materials toward industrial application.

Keywords: Microalgal starch, Physicochemical properties, Thermoplastic starch, Bioplastic development, Sustainable feedstocks

1 Introduction

Plastic pollution has become a major global concern, with millions of tons entering marine environments every year and contributing to widespread microplastic contamination. This contamination affects ecological systems and poses growing risks to human health [1, 2]. The Global Plastics Outlook from the Organization for Economic Cooperation and Development indicates that about 353 million metric tons of plastic waste are produced each year, nearly one million metric tons per day. Only 9% of this waste is recycled. About half is sent to landfills, 19% is incinerated, and the remaining 22% (roughly 82 million metric tons per year) is openly burned, dumped in unsafe sites, or released directly into the environment [3]. A meaningful reduction in this environmental burden requires a shift toward materials that are both sustainable and less persistent in natural ecosystems. Expanding the production and use of bioplastics represents an important component of this transition. Many bioplastics possess inherent biodegradability, enabling them to break down into water, carbon dioxide, and biomass through natural biological

processes [4]. This degradability helps limit long term pollution and mitigates the accumulation of microplastics in both terrestrial and marine environments.

Starch is the most widely used precursor material in bioplastics manufacturing due to its renewability and abundance. A broad range of bioplastics, including thermoplastic starch (TPS), starch based blends, starch reinforced composites, and even polylactic acid (PLA), can be produced from it. Starch also possesses key physicochemical attributes such as thermoplastic behavior, chemical modifiability, and compatibility with fillers and polymer blends, which collectively make it a highly attractive material for sustainable plastic production [5, 6, 7]. For this application, it mainly comes from land crops such as corn, wheat, rice, potato, cassava, and sweet potato, which remain the primary industrial sources. However, reliance on these feedstocks presents several challenges, including competition for arable land, seasonal and geographic variability, high freshwater requirements, and the broader food versus materials debate [8, 9, 10]. These limitations have intensified interest in identifying alternative and more sustainable starch sources. In this context, increasing attention has been directed toward organisms such as microalgae, which accumulate substantial quantities of starch as a primary carbon sink and can be cultivated without competing with food production systems.

Microalgae are unicellular eukaryotic microorganisms capable of oxygenic photosynthesis and are predominantly distributed across aquatic ecosystems. They function as major primary producers and are central to global nutrient and carbon cycling, contributing approximately 50% of the Earth's oxygen output [11]. Comparative physiological studies demonstrate that microalgae exhibit higher photosynthetic efficiency than terrestrial plants [12, 13] and possess 10-50 fold greater carbon-fixation capacity [14, 15], reflecting their exceptional metabolic productivity. They further exhibit broad ecological tolerance, thriving in environments as varied as wastewater and freshwater systems, marine and hypersaline habitats, as well as desert and polar regions [16]. This adaptability, combined with their metabolic plasticity, enables targeted modulation of biochemical pathways; for example, controlled variation in cultivation parameters is widely used to enhance starch accumulation in specific strains [17]. In addition, their relatively simple cellular organization facilitates genetic manipulation, making microalgae particularly amenable to metabolic engineering with current advanced molecular tools [18, 19]. Another notable advantage of microalgae as a starch feedstock is that they lack lignin in their cellular structure [20]. In terrestrial plants and seaweeds, lignin complicates pretreatment by generating compounds that inhibit hydrolysis and restrict the growth of fermentative microorganisms. The lack of lignin in microalgae therefore removes a major barrier in biomass deconstruction, enabling more efficient starch recovery and conversion to bioplastics [21].

Microalgae represent an exceptionally diverse group of photosynthetic microorganisms, with global species richness estimated to range from 200,000 to 800,000, although only about 50,000 have been formally identified [22, 23]. They synthesize a wide array of metabolites, including carbohydrates, lipids, proteins, and pigments, each with distinct industrial relevance [24]. Consequently, once starch is extracted from microalgal biomass, the remaining metabolites can be valorized for additional applications, enabling integrated biorefinery approaches and improving overall resource efficiency [25]. Beyond their biochemical versatility, microalgae offer several practical advantages as a biomass feedstock. They do not require arable land, demand substantially less water and fertilizer than terrestrial crops, and exhibit high biomass productivity with short cultivation cycles [26, 27]. Their growth is not constrained by seasonal variation, enabling continuous production throughout the year [28]. Microalgae can be cultivated in photobioreactors or open ponds, where water can be recycled and reused multiple times, reducing operational inputs [29]. Many species can also grow on wastewater, which minimizes the need for additional nutrients and supports wastewater bioremediation [30]. Furthermore, microalgal cultures can be

harvested repeatedly from the same growth medium, contributing to high cumulative biomass yields. Under favorable cultivation conditions, they complete their growth cycle much faster than conventional plant feedstocks, which enhances their efficiency and scalability as a source of starch for bioplastic production [31, 32, 33].

Despite these advantages, several constraints persist across the microalgal starch production chain. Starch is enclosed within very small cells with robust walls, so efficient recovery requires intensive mechanical or physicochemical disruption. During extraction, proteins, pigments, lipids, and cell debris are released, which increases purification complexity and reduces process selectivity [34]. Cultivation also imposes substantial energy demand. Circulation in raceway ponds, pumping in photobioreactors, harvesting and drying of biomass, and subsequent extraction and purification steps all require considerable electricity, which elevates both operational cost and environmental burden [35]. Cost assessments illustrate this challenge, with reported production values ranging from 2.90 € kg⁻¹ to 290 € kg⁻¹ depending on strain, cultivation regime, and processing configuration [36, 37, 38]. These values remain significantly higher than those associated with terrestrial starch crops. Environmental impacts follow the same trend. Producing protein from *Chlorella vulgaris* results in 126.3-264.3 kg CO₂ equivalent, compared with 4-10 kg CO₂ equivalent for pea [39]. Nevertheless, current studies indicate that future optimization of cultivation, harvesting, and extraction strategies may reduce these constraints and improve overall feasibility [40].

In recent years, the extraction and utilization of microalgal starch for bioplastic production has emerged as a rapidly expanding research frontier. Beyond its sustainability advantages, microalgal starch exhibits distinctive physicochemical characteristics that differentiate it from starches derived from terrestrial plants. These include very small granule size with narrow size distribution [41], species dependent crystalline organization [42], and intermediate gelatinization behavior [43], each of which can influence polymer processing and material performance. Collectively, these attributes provide opportunities to engineer next generation biodegradable materials with tailored thermal, mechanical, and structural properties, positioning microalgal starch as a promising feedstock for advanced bioplastic design and functional biomaterials [44]. Although the bioplastic potential of microalgal starch is increasingly recognized as a mandatory research direction, there is, to the best of our knowledge, no dedicated review that clearly consolidates current understanding of its physicochemical properties across different strains and how these properties shape material behavior relative to crop starches. Accordingly, this article provides a critical synthesis of current knowledge on microalgal starch, with emphasis on physicochemical attributes that govern material performance. It examines how molecular architecture, thermal transitions, and structural organization influence the functionality of starch based systems. It further evaluates emerging conversion pathways for producing microalgal starch derived bioplastics and identifies key limitations and knowledge gaps that must be addressed to advance these materials toward industrially viable, high performance applications. Literature is synthesized critically, with studies selected for their relevance to native starch behavior and bioplastic formation.

2 Physicochemical properties of microalgal starch

2.1 Granule morphology

Microalgal starches have been examined across a wide range of physicochemical attributes, including structural, thermal, and rheological behavior. Among the structural parameters, granule morphology remains the most consistently characterized feature. Microalgal species typically contain very small starch granules, with mean diameters often below 2 μm [45]. This contrasts with crop starches, which generally range from 5 to 100 μm. Microalgal starches are further

noted for their comparatively narrow particle size distribution. For instance, Liao et al. [46] showed that *Tetraselmis subcordiformis* starch displays poly dispersity index (PDI) values between 0.39 and 0.21, indicating a highly uniform granule population. A comparable pattern was reported by Di Caprio et al. [47], who found that 95% of *Tetradesmus obliquus* granules fall within a narrow interval of 0.645 to 1.215 μm . Such small granule dimensions contribute to a relatively high surface area to volume ratio. This provides more accessible sites for plasticizer interaction and promotes faster, more uniform gelatinization due to shorter diffusion pathways. It also increases the starch's susceptibility to enzymatic or chemical modification, which enhances its suitability for bioplastic applications [48]. In terms of shape, starch granules from microalgae are predominantly ellipsoidal and spherical, often exhibiting slight surface wrinkles and minor irregularities, although discoidal granules have also been reported for *Chlorella kessleri* [49] and *Chlamydomonas reinhardtii* [50]. Table 1 summarizes the average granule sizes reported for microalgal starches across various studies.

Table 1: Average granule sizes of microalgal starches reported across multiple studies.

Starch source	Mean dia (μm)	Ref.
<i>T. subcordiformis</i>	1.51	[46]
<i>C. reinhardtii</i>	1.0	[50]
<i>T. obliquus</i>	0.93	[47]
<i>C. vulgaris</i>	1.5	[51]
<i>K. flaccidum</i>	1.0	[52]
<i>C. sorokiniana</i>	1.5	[53]
<i>C. vulgaris</i>	1.12	[54]
<i>C. pyrenoidosa</i>	1.10	[48]
<i>C. ellipsoidea</i>	1.24	
<i>C. luteorividis</i>	1.29	
<i>C. protothecoides</i>	1.26	
<i>C. sorokiniana</i>	1.27	
<i>Chlorella sp.</i>	1.02	[55]
<i>Chlorella sp.</i>	0.8-1.2	[56]

2.2 Crystalline and molecular structure

The crystal structure most commonly reported for microalgal starch is A-type, a polymorph characterized by tightly packed double helices and relatively low water content within the crystalline lamellae [57, 50]. This arrangement reflects a structure typically found in cereal starches, highlighting a close resemblance between microalgal starch and crop-derived starches. Some studies have also identified V-type crystallinity, which arises from the formation of amylose-lipid inclusion complexes and indicates the presence of endogenous lipids within the granules [56]. On the other hand, relative crystallinity values reported for microalgal starches are generally slightly lower than those of crop-derived starches. Across different strains, microalgal starch typically shows 21-35% relative crystallinity, whereas crop starches commonly range from 21.5% for rice starch to 37% for corn starch. Among microalgae, the highest values have been reported for *Chlamydomonas reinhardtii* at 34.9% [50], followed by *Tetraselmis subcordiformis* at 30.9% [46], *Chlorella sorokiniana* at 30% [53], and *Chlorella sp. MBFJNU-17* at 25.93% [55]. These observations indicate that microalgal starch contains a relatively smaller fraction of ordered,

crystalline regions compared with crop starches. This is further supported by the significantly lower ratios of absorbance at $R_{1047/1022}$ and $R_{995/1022}$ obtained for *Chlamydomonas reinhardtii* by Xu et al. [50] from Fourier transform infrared spectroscopy (FTIR) analysis, which reflect reduced short-range molecular order. These spectral features confirm that microalgal starch possesses a higher proportion of amorphous regions than terrestrial crop starches, a finding also reported by Jiang et al. [58] for *Chlorella sorokiniana*. A lower proportion of crystalline domains improves bioplastic conversion because amorphous regions hydrate, swell, and gelatinize more readily. This accelerates thermal softening, enhances plasticizer penetration, and promotes uniform melt formation during thermoplastic starch processing. Reduced crystallinity also increases susceptibility to chemical or enzymatic modification, allowing easier tuning of flexibility, polymer compatibility, and degradability. Consequently, microalgal starch can be processed at lower temperatures and shorter residence times than crop starches, reducing energy demand and improving material homogeneity.

The variation in the properties of microalgal starch is expected and reflects several underlying factors, including species-specific biochemical traits, cultivation conditions, and the extraction and purification methods employed. This is clearly illustrated by the work of Liao et al. [46], who reported substantial differences in relative crystallinity for *Tetraselmis subcordiformis* when varying ultrasonication intensity and duration, as well as the phase from which starch was recovered in aqueous two phase systems (ATPS). Depending on whether starch was collected from the bottom (USB) or interface (USI) phase and on the ultrasonication conditions (200 or 300 W for 10–25 min), crystallinity ranged from 18.2 to 30.9%. The lowest value occurred for USB at 300 W for 15 min, whereas the highest was recorded for USI at 300 W for 15 min. They also showed that ultrasonication duration increased the $R_{1047/1022}$ ratio for both power levels, while higher power significantly reduced this ratio. Additionally, the influence of cultivation conditions on relative crystallinity was reported by Chi et al. [56], who examined *Chlorella sp. MBFJNU-17* under heterotrophic cultivation. Starch produced during nitrogen supplementation for 72 h exhibited the lowest crystallinity (21.70%), whereas nitrogen starvation for 40 h yielded starch with the highest crystallinity (26.20%). These results highlight that both processing conditions and metabolic state with nutrient availability modulate short-range molecular order and crystallinity, ultimately shaping the functional properties of microalgal starch.

Furthermore, the amylose content reported for microalgal starch (13–25.61%) is comparable to that of terrestrial crop starches, which typically range from 13.87 to 27.91% [53, 58]. Ramli et al. [52] compared the amylose content of *Klebsormidium flaccidum* starch with corn starch and found that the microalgal starch contained slightly more amylose (25.52% vs 23.04%). This higher amylose fraction was associated with lower swelling power and solubility than corn starch, as well as reduced moisture content (24.8% vs 50.8%), likely due to the tighter molecular packing and more restricted hydration of amylose-rich granules. Conversely, Xu et al. [50] reported that *Chlamydomonas reinhardtii* starch contains less amylose than corn, wheat, and maize starches, and exhibits a notably higher degree of amylopectin branching (18.6%). This indicates that structural composition can vary substantially among microalgal species.

On the other hand, the thickness of semicrystalline lamellae in microalgal starch is reported to be slightly lower than that of crop starches. This reduced lamellar thickness contributes to the lower gelatinization temperature and enthalpy observed for microalgal starch compared with terrestrial starches. Jiang et al. [58] confirmed this by demonstrating that *Chlorella sorokiniana* starch exhibits a smaller semicrystalline interlamellar layer thickness (9.28 nm) than corn (9.66 nm), wheat (9.54 nm), and quinoa (9.68 nm) starches, while still exceeding the values reported for potato (9.18 nm) and rice (9.10 nm) starches. Similar to other structural attributes, lamellar thickness is influenced by species, cultivation conditions, and cultivation duration. For instance,

Jiang et al. [48] compared semicrystalline interlamellar distances among several *Chlorella* strains, including *C. pyrenoidosa*, *C. ellipsoidea*, *C. luteorividis*, *C. protothecoides*, and *C. sorokiniana*, and reported values of 9.51, 9.36, 9.43, 9.18, and 9.33 nm, respectively. Additionally, Chi et al. [56] demonstrated that lamellar thickness increases with cultivation duration. For *Chlorella sp. MBFJNU-17* grown under nitrogen deprivation, lamellar thickness rose from 8.97 nm after 16 h to 9.15 nm after 40 h. Similarly, when nitrogen was supplemented, cultivation for 8 h produced a thickness of 9.15 nm, whereas extending cultivation to 72 h resulted in a larger value of 9.37 nm. This indicates that nutrient availability and cultivation time jointly modulate the development of semicrystalline lamellae in microalgal starch. Regarding amylopectin chain-length distribution, microalgal starches are also reported to possess longer chains. Jiang et al. [58] showed that *Chlorella sorokiniana* starch contains longer amylopectin chains than corn, rice, wheat, and quinoa starches, with values slightly lower than those of potato starch. For chains with a degree of polymerization (DP) ≥ 37 (B3 chain), the alga starch contained 10.51%, whereas corn, rice, wheat, quinoa, and potato starches contained 7.49, 7.91, 7.54, 8.17, and 11.43%, respectively. For DP 25–36 (B2 chain), the corresponding values were 15.09, 15.9, 12.26, 11.94, 12.76, and 16.71%, respectively. A similar observation was reported by Chi et al. [55], who found that *Chlorella sp. MBFJNU-17* also exhibits longer amylopectin chain lengths (23.57%) compared with quinoa starch (18.58%) for the B3 chain. Additionally, the effect of cultivation duration on average molecular weight (Mw), amylose and amylopectin chain-length distribution (DP), and degree of branching (DB) was further examined by the same researchers for the alga starch. They reported that starch produced under nutrient-starvation for an extended period (40 h) exhibited the highest Mw, B3 chain, and DB, with values of 1.71×10^7 Da, 23.04%, and 11.80%, respectively. However, the amylose chains were relatively shorter, indicating that prolonged nutrient limitation promotes the formation of highly branched, high-molecular-weight amylopectin while suppressing amylose chain elongation. Table 2 summarizes the reported amylose content, relative crystallinity, and interlamellar thickness of starches from different microalgal species across multiple studies.

Table 2: Amylose content, relative crystallinity, and interlamellar thickness (d) of starches from different microalgal species.

Starch source	Amylose content (%)	Relative crystallinity (%)	d (nm)	Ref.
<i>C. reinhardtii</i>	-	34.9	9.29	[50]
<i>C. vulgaris</i>	13.0	-	9.50	[51]
<i>C. pyrenoidosa</i>	24.92	22.19	9.51	[48]
<i>C. ellipsoidea</i>	25.61	21.10	9.36	
<i>C. luteorividis</i>	23.33	25.28	9.43	
<i>C. protothecoides</i>	24.15	23.98	9.18	
<i>C. sorokiniana</i>	22.90	21.36	9.33	
<i>K. flaccidum</i>	25.52	-	-	[52]
<i>C. sorokiniana</i>	17.0	30.0	-	[53]
<i>Chlorella sp.</i>	13.45	25.93	9.16	[55]
<i>Chlorella sp.</i>	-	26.20	9.15	[56]
<i>C. sorokiniana</i>	19.22	21.68	9.28	[58]

2.3 Gelatinization behavior

Studies on the gelatinization temperature of microalgal starch report variable results, although most consistently agree that its gelatinization enthalpy is lower than that of crop starch. For example, Gifuni et al. [53] demonstrated a wide gelatinization temperature range for *Chlorella sorokiniana*. They reported an onset temperature (T_{on}) of 24 °C, a peak temperature (T_p) of 69 °C, and a conclusion temperature (T_c) of 97 °C, accompanied by a ΔH of 5.49 J/g. On the other hand, Chi et al. [55] compared *Chlorella sp. MBFJNU-17* starch with quinoa starch and observed that the microalgal starch exhibits higher thermal stability during hydrothermal treatment. *Chlorella* starch gelatinized at T_{on} 63.05 °C, T_p 66.34 °C, and T_c 74.07 °C, whereas quinoa starch gelatinized at T_{on} 54.77 °C, T_p 60.05 °C, and T_c 67.27 °C. They also reported a slightly higher enthalpy for *Chlorella* starch (8.82 J/g vs 8.09 J/g), indicating that its molecular structure is more ordered and therefore requires greater energy input to disrupt. Conversely, Jiang et al. [58] reported a much lower enthalpy for *Chlorella sorokiniana* starch (4.42 J/g) compared with potato (16.42 J/g), corn (14.57 J/g), rice (5.46 J/g), wheat (14.43 J/g), and quinoa starch (4.86 J/g). Similarly, Xu et al. [50] reported lower enthalpy values for *Chlamydomonas reinhardtii* starch relative to corn, wheat, maize, potato, and sweet potato starches. They observed gelatinization temperatures of T_{on} 63.0 °C, T_p 73.2 °C, and T_c 84.1 °C for the microalgal starch. This supports the trend that microalgal starches generally require less energy to disrupt their semicrystalline structure than most terrestrial starches.

As with other physicochemical properties, gelatinization temperature and enthalpy are strongly influenced by species, cultivation conditions, and extraction technique. Jiang et al. [58] reported higher gelatinization temperatures for *Chlorella protothecoides* and the lowest values for *Chlorella sorokiniana* among *Chlorella pyrenoidosa*, *Chlorella ellipsoidea*, and *Chlorella luteorividis*. Additionally, Liao et al. [46] reported higher gelatinization temperatures when ultrasonication was performed at 300 W for 25 min and starch was collected from the bottom phase of the ATPS system, whereas the lowest temperatures were observed at 200 W for 10 min for starch recovered from the same phase for *Tetraselmis subcordiformis*. Longer cultivation under nitrogen supplementation has also been shown to increase gelatinization temperature, with *Chlorella sp. MBFJNU-17* exhibiting its highest values when grown for extended periods under nutrient-rich conditions [56]. Izumo et al. [49] further demonstrated that CO₂ availability modulates gelatinization behavior in *Chlorella kessleri*, where high CO₂ supplementation (3%) yielded a higher gelatinization temperature (75.0 °C) compared with low CO₂ (0.04%, 67.4 °C). Table 3 summarizes the gelatinization temperatures of starches from different microalgal species reported across various studies.

2.4 Rheological property

The pasting property of microalgal starch has been compared with various crop starches and is consistently found to exhibit a distinct rheological profile. For instance, Jiang et al. [58] compared peak (Pv), trough (Tv), breakdown (Bv), final (Fv), and setback viscosity (Sv) of *Chlorella sorokiniana* starch with potato, corn, rice, wheat, and quinoa starches. They found that the microalgal starch displayed a markedly lower peak viscosity (262 cp) than potato (5021 cp), corn (920 cp), and wheat (521 cp) starches. It also exhibited substantially lower breakdown viscosity (19 cp) compared with potato (3013 cp), corn (142 cp), wheat (180 cp), and rice (142 cp), indicating lower swelling capacity and greater resistance to shear than those crop starches. The trough viscosity of *Chlorella sorokiniana* starch (244 cp) was likewise lower than potato (2009 cp), corn (775 cp), and wheat (341 cp) starches. This demonstrates that the algal starch is structurally weaker than those starches, while being stronger than rice (99 cp) and quinoa starches (236 cp). Potato, corn, and wheat starches also exceed the algal starch

Table 3: Gelatinization temperatures of starches from different microalgal species.

Starch source	T _{on} (°C)	T _p (°C)	T _c (°C)	ΔH (J/g)	Ref.
<i>T. subcordiformis</i>	65.9	68.6	73.3	12.1	[46]
<i>C. reinhardtii</i>	63.0	73.2	84.1	-	[50]
<i>C. vulgaris</i>	-	65	-	-	[51]
<i>C. pyrenoidosa</i>	64.62	69.54	76.45	6.23	[48]
<i>C. ellipsoidea</i>	65.27	70.82	77.11	8.03	
<i>C. luteorividis</i>	65.76	71.51	78.34	10.47	
<i>C. protothecoides</i>	66.86	72.03	78.88	9.40	
<i>C. sorokiniana</i>	63.57	67.41	74.5	8.01	
<i>C. sorokiniana</i>	24.0	69.0	97.0	5.49	[53]
<i>Chlorella sp.</i>	63.05	66.34	74.07	8.82	[55]
<i>Chlorella sp.</i>	71.12	-	83.27	9.62	[56]
<i>C. sorokiniana</i>	62.56	66.77	71.60	4.42	[58]

in gel-forming capacity, as reflected by their substantially higher final viscosity values. From the setback viscosity profile, *Chlorella sorokiniana* starch retrogrades more slowly than wheat, potato, and rice starches but faster than corn and quinoa starches, suggesting a greater tendency to form more brittle bioplastic films than the latter. Xu et al. [50] reported similar findings for *Chlamydomonas reinhardtii* starch when compared with corn, wheat, maize, potato, and sweet potato starches, showing that microalgal starch generally exhibits lower swelling capacity, weaker structural strength, lower gel-forming ability, higher thermal stability, greater shear resistance, and slower retrogradation than those crop starches. Chi et al. [55] further demonstrated that *Chlorella sp.* MBFJNU-17 starch exhibits a higher pasting temperature (67.18 °C vs 59.69 °C) than quinoa starch, indicating greater granule stability and crystallinity. They also showed that it retrogrades faster due to its higher setback viscosity (53.50 cp vs 44.50 cp). Strain-level variation in pasting behaviour has also been documented. Jiang et al. [48] showed that *Chlorella protothecoides* starch displays rheological properties more comparable to crop starches than other microalgal strains, with Pv 530 cp, Tv 503 cp, Fv 1057 cp, and Sv 554 cp. Despite this resemblance, its low breakdown viscosity (27 cp) indicates notable resistance to heat and shear. Table 4 summarizes the pasting parameters reported in studies and highlights the consistent differences between microalgal and crop starches.

The steady shear data further demonstrate the shear-resistant nature of microalgal starch. Jiru et al. [54] reported that *Chlorella vulgaris* starch shows a higher flow behavior index ($n = 0.67$) than crop starches (0.30–0.45), indicating a more gradual viscosity decay under shear. In contrast, its consistency index ($K = 59.47 \text{ Pa}\cdot\text{s}^n$) and apparent viscosity at 1 s^{-1} ($\approx 400 \text{ Pa}\cdot\text{s}$) are markedly lower than those of crop starches (118–4000 $\text{Pa}\cdot\text{s}^n$ and 400–7500 $\text{Pa}\cdot\text{s}$, respectively). Crop starches form more viscous pastes at low shear than microalgal starch because their larger granules and higher amylose content promote extensive swelling and network development. Yet these swollen structures collapse rapidly under shear, producing pronounced shear-thinning. In contrast, microalgal starch, although less viscous initially, retains structural integrity more effectively under shear, confirming its inherently higher shear resistance. Additionally, *Chlorella vulgaris* starch shows an intermediate yield stress ($\tau_0 = 271.93 \text{ Pa}$), lower than corn starch ($\approx 800 \text{ Pa}$) but higher than rice starch ($\approx 191 \text{ Pa}$). This reflects its finer granule size and lower amylose content relative to corn starch, yet greater network strength than rice starch. Jiang

Table 4: Comparison of pasting characteristics between microalgal and terrestrial starches.

Starch source	Pv (cp)	Tv (cp)	Fv (cp)	Bv (cp)	Sv (cp)	Ref.
Potato	5278	1574	1745	3704	23	[50]
Sweet potato	2375	1541	1852	834	311	
Corn	1881	966	1329	915	363	
Maize	863	802	874	61	72	
Wheat	637	437	671	200	233	
<i>C. reinhardtii</i>	493	484	542	8	58	[48]
<i>C. sorokiniana</i>	401	389	567	12	178	
<i>C. luteorividis</i>	522	453	1007	69	554	
<i>C. ellipsoidea</i>	464	424	893	40	469	
<i>C. protothecoides</i>	530	503	1057	27	554	
<i>C. pyrenoidosa</i>	447	436	890	12	454	[58]
<i>C. sorokiniana</i>	262	244	384	19	141	

et al. [58] similarly showed that *Chlorella sorokiniana* starch forms weaker gel networks than corn and wheat starches, as indicated by its lower elastic (G') and loss (G'') moduli. However, consistent with crop starches, the microalgal starch maintained $G' > G''$ across $0.1\text{--}100\text{ rad s}^{-1}$, confirming its predominantly elastic behavior. A broader comparison across *Chlorella* strains further highlights the diversity of microalgal rheology. Jiang et al. [48] observed shear-thinning in all examined strains, but the extent of structural stability varied markedly. *Chlorella protothecoides* exhibited the highest apparent viscosity, indicating a more robust granular network, whereas *Chlorella pyrenoidosa* showed pronounced structural breakdown under shear and slow recovery. In a related study, Jiang et al. [57] reported that although all strain starches displayed pseudoplastic behavior, *Chlorella sorokiniana* starch had the lowest apparent viscosity and the weakest ability to withstand and recover from shear. These inter-strain differences underscore that, although shear-thinning is a common feature of microalgal starches, their resistance to deformation and ability to rebuild structure are strongly species-dependent.

3 Microalgal starch as a bioplastic material

Research on TPS derived from microalgae remains limited, with only a few studies evaluating its processability and mechanical performance when plasticized with glycerol. Six et al. [51] demonstrated that *Chlorella vulgaris* starch (purity 86.9%) is readily extrudable, particularly at $120\text{ }^{\circ}\text{C}$ with 30% glycerol, confirming its suitability for TPS formation. They further molded the material into dogbone specimens and compared its mechanical properties with potato based TPS and commercial TPS. Microalgal TPS showed markedly higher elongation at break (158%) than potato TPS (120%) and commercial TPS (78%), indicating a more ductile deformation profile. However, its tensile strength (0.5 MPa) and Young's modulus (1.2 MPa) were substantially lower than those of potato TPS (2.9 and 15.4 MPa) and commercial TPS (3.5 and 30 MPa). The authors attributed this reduced stiffness and strength to the lower amylose content of *Chlorella vulgaris* starch (13%) compared with potato starch (typically 20–25%). A similar trend was reported by Di Caprio et al. [59], who examined TPS films produced from *Tetrademus obliquus* starch (81% purity) blended with chitosan. They found that alga derived TPS exhibited considerably lower tensile strength and Young's modulus than corn starch based TPS containing chitosan. However, the alga TPS displayed higher elongation at break and

toughness compared with corn TPS, reinforcing the observation that microalgal starch produces more ductile but less rigid TPS matrices. In contrast, their subsequent study using the same species but lower starch purity (57%) [60] showed that microalgal TPS exhibited much lower elongation at break (9.5%) than corn TPS (40%) and a higher soluble fraction. This reduction in mechanical performance was attributed to the greater proportion of non-starch impurities, which disrupt network formation and weaken the TPS matrix. Despite these differences, both algal and corn TPS displayed similar thermal degradation profiles, with initial mass loss from 60–100 °C due to residual moisture and major starch decomposition occurring between 300–320 °C. Table 5 compares the properties of thermoplastic starch films produced from *Tetradesmus obliquus* starch (81% purity) and corn starch, both formulated with 10% w/w glycerol and 2% w/v chitosan.

Table 5: Comparison between properties of microalgal and corn starch derived TPS films [59].

Properties	<i>T. obliquus</i> TPS	Corn TPS
Tensile strength (MPa)	22.0	40.9
Young's modulus (MPa)	8.5	15.7
Elongation at break (%)	16.4	7.0
Toughness (MPa)	3.5	2.8

4 Challenges and future prospects

Microalgal-starch-derived bioplastics face several processing-related challenges that currently limit their broader technological adoption. Recovering starch from microalgae remains costly because cell disruption requires sophisticated equipment capable of breaking rigid cell walls, often through high-energy methods such as bead milling, ultrasonication, or high-pressure homogenization [61]. During extraction, numerous intracellular metabolites are released alongside starch, complicating purification and making the attainment of high-purity starch a technically demanding and expensive process [34]. These purity limitations directly influence material performance. Additionally, because microalgal starch typically yields more ductile behavior, its load-bearing capacity is lower than that of crop starch derived plastics [51, 59]. The absence of standardized processing protocols, together with limited rheological and thermal datasets across species, further restricts the ability to optimize formulations and predict material behavior. Furthermore, the scarcity of comprehensive techno-economic and life-cycle assessments hinders realistic evaluation of industrial feasibility and environmental impact.

Despite these constraints, microalgal-starch-based bioplastics present opportunities for further exploration. Ongoing work in strain engineering, controlled nutrient modulation, and photobioreactor operation may improve starch accumulation and help lower production costs, although the extent of these gains remains uncertain. Advances in cell disruption and purification could also support the generation of higher-purity starch streams suitable for thermoplastic processing. Microalgal starch provides fermentable glucose without dependence on agricultural land or freshwater, which makes it a possible feedstock for PLA synthesis. In addition, combining microalgal-derived PLA with chitosan or nanofillers may offer routes to adjust mechanical performance and expand application space. As sustainability pressures intensify, microalgal starch could become a relevant feedstock within the bioplastics sector. Future research must still address gaps in structure-property relationships and process economics to clarify its industrial feasibility.

5 Conclusion

Microalgal starch shows a distinct combination of fine granule size, reduced crystallinity, longer amylopectin chains, and species-specific thermal and rheological behavior. These features set it apart from terrestrial starches and create clear opportunities for bioplastic development. The small granules and high amorphous fraction promote rapid gelatinization and stronger interactions with plasticizers. Its lower enthalpy and shear-resistant pasting behavior also support energy-efficient processing and stable thermoplastic formation. Additionally, thermoplastic starch from microalgal sources generally displays lower strength, yet it consistently shows higher elasticity and toughness than crop-derived TPS. This is advantageous for applications where flexibility is more important than load-bearing capacity. Moreover, mechanical performance can be further improved through blending, for example with additives such as chitosan. Despite these advantages, several challenges remain. High-energy cell disruption, variability in starch purity, and limited techno-economic evaluation continue to constrain broader adoption. Progress in cultivation control, strain engineering, extraction efficiency, and composite formulation is therefore essential. Finally, current evidence indicates that microalgal starch is a technically promising and environmentally aligned feedstock for next-generation bioplastics. It has strong potential to complement or replace crop-derived starches as processing strategies mature and industrial scalability improves.

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