Journal of Innovative Agriculture
Review Article

Utilization of pineapple wastes for production of microbial pigments: extraction technologies, industrial applications, techno-economic and lifecycle assessment

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Volume: 12, Issue: 4, Pages: 10-35
DOI: https://doi.org/10.37446/jinagri/ra/12.4.2025.10-35
Received: 1 August 2025 / Accepted: 4 November 2025 / Published: 31 December 2025

The escalating demand for natural pigments, driven by their eco-friendly and bioactive properties, has spotlighted microbial production as a sustainable alternative to synthetic dyes. Pineapple wastes (PAWs), comprising 45–55% of the fruit's weight, are rich in fermentable sugars and bioactive compounds, making them ideal substrates for microbial pigment synthesis. This review comprehensively explores the production of pigments like carotenoids, anthocyanins, and prodigiosins using PAWs, leveraging bacteria, fungi, yeasts, and microalgae. Advanced extraction technologies, including supercritical CO_2, ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), ionic liquids (ILs), and enzyme-assisted extraction, are critically evaluated for their efficiency and sustainability. Industrial applications span food, cosmetics, textiles, and pharmaceuticals, with techno-economic assessments (TEA) and life cycle assessments (LCA) highlighting scalability and environmental benefits. Recent data from 2024–2025 underscore PAW's up to a projected 60% cost reduction under optimal scale-up conditions and greenhouse gas emissions by 50% compared to synthetic methods. Challenges such as high equipment costs, regulatory hurdles, and process optimization are addressed, emphasizing the role of PAW valorization in advancing a circular bioeconomy. This review highlights the potential of pineapple waste-derived pigments to drive a circular bioeconomy while identifying research gaps for industrial implementation.

Keywords: *pineapple waste, microbial pigments, extraction technologies, industrial applications, techno-economic assessment, lifecycle assessment*

Introduction

Microbial pigments, synthesized by bacteria, fungi, yeasts, and microalgae, have emerged as sustainable, eco-friendly alternatives to synthetic dyes, addressing environmental, health, and economic concerns associated with chemical colorants. These natural pigments, encompassing carotenoids, monascins, violacein, prodigiosin, phycocyanins, and melanins, offer vibrant colors ranging from yellow and red to blue and violet, alongside bioactive properties such as antioxidant, antimicrobial, anticancer, and anti-inflammatory activities. Their biodegradable, non-toxic nature makes them ideal for diverse applications in food, pharmaceuticals, cosmetics, textiles, and biotechnology, where they serve as both colorants and functional ingredients (Grewal et al., 2022). The global market for natural pigments, including microbial sources, was valued at \$1.7 billion in 2023 and is projected to reach \$2.5 billion by 2027, growing at a compound annual growth rate of 10.2%, driven by consumer demand for clean-label, sustainable, and health-conscious products (de Oliveira et al., 2024). This surge reflects a broader shift toward environmentally responsible production, with microbial pigments playing a pivotal role in reducing reliance on petroleum-based dyes linked to pollution and health risks like allergies and hyperactivity. The production of microbial pigments using agro-industrial wastes, particularly pineapple by-products, aligns with the principles of a circular bioeconomy, transforming abundant, low-cost waste into high-value products while mitigating environmental degradation. Pineapple, a tropical fruit cultivated extensively in countries like Costa Rica, the Philippines, and Thailand, generated 29.4 million tons globally in 2023, with 50–60% of its weight approximately 14.7–17.6 million tons discarded as peels, cores, crowns, and pomace (Tropea et al., 2025). Traditionally landfilled or incinerated, these wastes contribute to greenhouse gas emissions, including methane, and environmental pollution. However, their rich composition, including fermentable sugars like glucose and fructose, dietary fibers, and bioactive compounds such as phenolic acids and bromelain, makes them an ideal substrate for microbial fermentation. Microorganisms such as *Monascus purpureus, Rhodotorula mucilaginosa, Chromobacterium violaceum,* and *Xanthophyllomyces dendrorhous* utilize these nutrients as carbon and nitrogen sources to produce pigments like red monascins, yellow carotenoids, violet violacein, and red astaxanthin (Polania et al., 2023). For instance, a 2022 study demonstrated that *Rhodotorula mucilaginosa* fermented pineapple peel to produce β-carotene at a cost of \$5.04/g, compared to \$10.40/g for synthetic β-carotene, highlighting the economic potential of waste valorization (Li et al., 2022). Similarly, a 2022 study showed that *Chromobacterium violaceum* produced violacein using liquid pineapple waste, reducing costs by 16%; from \$281.20 to \$235.70 per unit compared to nutrient broth (Gohil et al., 2022). By leveraging pineapple wastes, these bioprocesses address the high cost of fermentation substrates, a major bottleneck in scaling microbial pigment production, while supporting United Nations' Sustainable Development Goals, particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) (Sarangi et al., 2023). The diversity of microbial pigments underscores their versatility. Carotenoids, including β-carotene, lycopene, and astaxanthin, are produced by bacteria like *Rhodopseudomonas faecalis*, yeasts like *Rhodotorula mucilaginosa*, and microalgae like *Chlorella minutissima*. These yellow-to-red pigments are valued for their antioxidant properties and applications in food (e.g., coloring beverages), cosmetics (e.g., UV-protective sunscreens), and pharmaceuticals (e.g., dietary supplements) (Kumaresan et al., 2025). A 2023 study reported a β-carotene yield of 12.5 mg/L from *Rhodotorula* on pineapple peel (Dutta et al., 2023). Monascins, red, yellow, and orange pigments from *Monascus purpureus*, are used in food (e.g., red yeast rice) and textiles, with a 2023 study achieving a 56.71 AU/50 mL yield using pineapple peel in solid-state fermentation (Barreto et al., 2023). Violacein, a violet pigment from *Chromobacterium violaceum*, exhibits antimicrobial and anticancer properties, with pineapple waste reducing production costs by 16%. Prodigiosin, a red pigment from *Serratia marcescens*, shows similar bioactivities, with a 2024 study exploring its pharmaceutical potential using pineapple waste (Anshi et al., 2024). Phycocyanins and phycoerythrins, blue and red pigments from cyanobacteria like *Spirulina platensis*, are used in food (e.g., natural blue colorants) and diagnostics (e.g., fluorescent markers), with a 2022 study optimizing phycocyanin production on pineapple pomace for a 20% yield increase (Banerjee et al., 2022). Melanins, brown-to-black pigments from fungi like *Aspergillus niger*, are applied in cosmetics for UV protection and biotechnology for biosensors, with a 2024 study noting their stability on pineapple waste substrates (Francis & Abdulhameed, 2024). These pigments vary in solubility, stability, and bioactivity, enabling tailored applications across industries.

Microbial pigment production involves complex biosynthetic pathways triggered by environmental factors like nutrient availability, pH, temperature, and light. For example, carotenoid synthesis in *Rhodotorula* relies on the mevalonate pathway, converting acetyl-CoA into isoprenoid precursors, while violacein production in *Chromobacterium violaceum* depends on tryptophan metabolism (Ramesh et al., 2025). Pineapple wastes enhance these processes by providing fermentable sugars (10–15% glucose, fructose in peels and pomace), fibers, and bioactive compounds like bromelain, which can stabilize pigments. A 2025 study found that bromelain in pineapple waste reduced pigment degradation in *Monascus purpureus* cultures by 15% during storage (Lee, 2025). Fermentation strategies, such as solid-state fermentation (SSF) and submerged fermentation (SmF), are tailored to the substrate and microorganism. SSF, using solid pineapple waste, minimizes water and energy use, while SmF suits liquid waste for high-yield extraction. Genetic engineering, including CRISPR-mediated pathway optimization, has boosted yields, with a 2023 study increasing *Rhodotorula β*-carotene production by 35% on pineapple peel through gene overexpression (Hussain et al., 2023). The environmental and economic advantages of microbial pigments are significant, particularly when using pineapple wastes. By diverting 14.7–17.6 million tons of annual pineapple waste from landfills, bioprocesses reduce methane emissions and pollution. A 2024 lifecycle assessment of a Costa Rican pineapple waste biorefinery estimated a 30% reduction in global warming potential compared to incineration (Paz-Arteaga et al., 2024). Economically, pineapple wastes are nearly cost-free, slashing substrate costs compared to synthetic media like glucose or yeast extract. A 2022 study reported a 90.88% cost reduction for carotenoid production by *Rhodopseudomonas faecalis* using pineapple waste and molasses, maintaining yields comparable to commercial media (Grewal, et al., 2022). Microbial pigments are biodegradable and produced *via* renewable processes, unlike synthetic dyes, which pollute waterways and require energy-intensive manufacturing. A 2024 study found that green extraction technologies, such as ultrasound-assisted extraction, reduced energy consumption by 25% compared to solvent-based methods (Zannou et al., 2025). These processes create closed-loop systems, with fermentation by-products like spent biomass used as animal feed or biofertilizers, enhancing resource efficiency and supporting a circular bioeconomy. Beyond coloration, microbial pigments offer bioactive functionalities that enhance their value. Carotenoids and phycocyanins neutralize free radicals, protecting against oxidative stress, with a 2024 study showing a 15% increase in antioxidant capacity in pear nectar using *Rhodotorula β*-carotene from pineapple waste (Sani et al., 2024). Violacein and prodigiosin inhibit pathogens like *Staphylococcus aureus* and *Escherichia coli*, with a 2024 study demonstrating that violacein extended food shelf life as a natural preservative (Guryanov & Naumenko, 2024). Prodigiosin and violacein also exhibit anticancer potential, with a 2024 study reporting prodigiosin's inhibition of breast cancer cell proliferation (Srilekha et al., 2024). Astaxanthin and phycocyanins reduce inflammation, with a 2023 study using astaxanthin from *Xanthophyllomyces dendrorhous* on pineapple waste in anti-inflammatory creams (Di Salvo et al., 2023). These properties position microbial pigments as dual-purpose ingredients, combining aesthetic and functional roles.

Industrially, microbial pigments are transforming multiple sectors. In food and beverages, they replace synthetic dyes like tartrazine, with *Rhodotorula* carotenoids enhancing yogurt's color and nutrition in a 2024 study (Thakur & Modi, 2024). In pharmaceuticals, prodigiosin and violacein are explored for drug development, with a 2024 study developing a prodigiosin-based antimicrobial coating for medical devices (Guryanov & Naumenko, 2024). In cosmetics, carotenoids and melanins are used in sunscreens and anti-aging products, with a 2021 study achieving 20% higher UV protection using astaxanthin from pineapple waste (Vishnupriya et al., 2021). In textiles, *Talaromyces purpureogenus* red pigment dyed cotton with 90% fastness and antioxidant properties in a study (Verma et al., 2023). In biotechnology, phycocyanins and melanins serve as biosensors and fluorescent probes, with a 2024 study improving diagnostic sensitivity using *Spirulina phycocyanin* from pineapple pomace (Silva et al., 2024). Market trends reflect consumer preference, with 68% of global consumers prioritizing clean-label products in 2023, supported by regulatory restrictions on synthetic dyes in the European Union (Mota et al., 2023). Pineapple wastes are critical to scaling microbial pigment production due to their abundance and nutrient richness. Peels and pomace contain 10–15% sugars, cores are rich in fibers and phenolic compounds, and crowns provide lignin and bromelain. Pretreatment methods like enzymatic hydrolysis and hydrothermal processing improve substrate accessibility, with a 2022 study reporting a 28% yield increase in *Rhodotorula* carotenoids after enzymatic pretreatment of pineapple pomace (Li et al., 2022). These advancements make pineapple wastes a scalable substrate, particularly in tropical regions. Despite progress, challenges remain. Production costs, driven by downstream processing like extraction and purification, are high, though green technologies like ultrasound-assisted extraction reduced costs by 25% in a 2023 study (Usman et al., 2023). Pigment stability under light, heat, and pH variations requires stabilization techniques, with a 2024 study improving *Rhodotorula* β-carotene shelf life by 40% through microencapsulation (Bera et al., 2024). Most studies are lab-scale, necessitating pilot-scale validation. Regulatory compliance with food and drug standards, such as FDA GRAS status, is critical. Future prospects include synthetic biology, with a 2024 study increasing astaxanthin production by 30% using CRISPR, and integrated biorefineries producing pigments, biofuels, and enzymes from pineapple waste (Mummaleti et al., 2025).

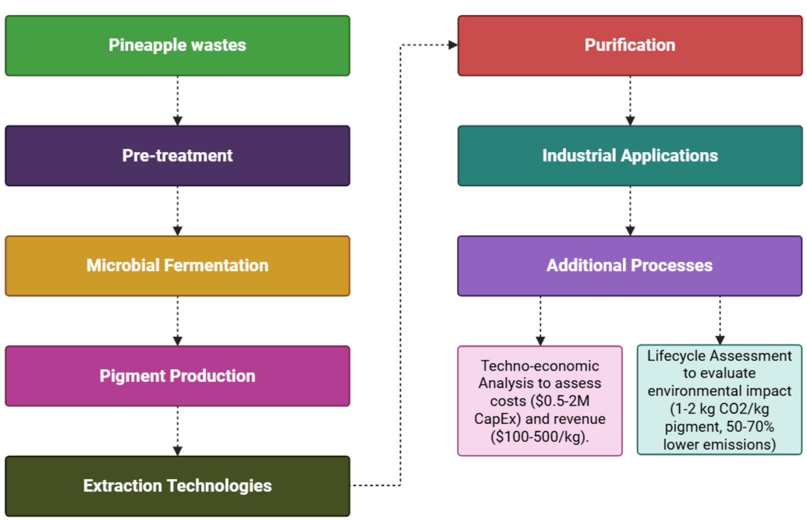

Figure 1. Integrated Biotechnological Approach for Pigment Production from Pineapple Waste: From Pre-treatment to Industrial Applications and Environmental Assessment

Advanced extraction and consumer education will further drive adoption. Pineapple waste serves as a cost-effective substrate for microbial fermentation, reducing reliance on expensive synthetic media like glucose or yeast extract shown in Figure 1. This review provides a comprehensive analysis of microbial pigment production from pineapple waste, with a focus on advanced extraction technologies, industrial applications, and detailed technoeconomic and lifecycle assessments. It incorporates recent data (2023–2025) and specific examples, such as the use of *Chromobacterium violaceum* for violacein production, to highlight practical applications. Challenges and future directions for scaling up these bioprocesses are also discussed, offering insights for researchers and industries aiming to adopt sustainable pigment production (Figure 1).

1. Pineapple wastes

Pineapple processing generates substantial waste, including peels (30–45%), cores (10–20%), crowns (3–6%), and pomace from juice extraction or canning (Table 1). These residues are rich in fermentable sugars like sucrose (5–10 g/L) and glucose (2–5 g/L), cellulose (20–25%), hemicellulose (15–20%), and bioactive compounds such as catechin (58.52 mg/100 g) and bromelain (Aili Hamzah et al., 2021).

Table 1. Chemical composition of pineapple waste fractions (peel, core, and crown)

Fraction	Component	Composition	Unit	Source
Peel	Holocellulose	36.8	% w/w	Roda et al. (2016)
	α-Cellulose	22.9	% w/w	Roda et al. (2016)
	Hemicellulose	13.9	% w/w	Roda et al. (2016)
	Lignin	5.1	% w/w	Roda et al. (2016)
	Water Content	86.5	% w/v	Roda et al. (2016)
	Cellulose	24.1 - 57.05	% w/w	Huang et al. (2011); Khedkar et al. (2017)
	Hemicellulose	9.73 - 29.3	% w/w	Huang et al. (2011); Khedkar et al. (2017)
	Lignin	6.3 - 20.45	% w/w	Huang et al. (2011); Khedkar et al. (2017)
	Ash	5	% w/w	Khedkar et al. (2017)
	Total Dietary Fiber (TDF)	45.22 ± 3.62	% w/w	Selani et al. (2014)
	Insoluble Dietary Fiber (IDF)	44.44 ± 3.60	% w/w	Selani et al. (2014)
	Soluble Dietary Fiber (SDF)	0.78 ± 0.10	% w/w	Selani et al. (2014)
	Carbohydrates	66 - 88	% w/w	Choonut et al. (2013)
Core	Holocellulose	29.5	% w/w	Roda et al. (2016)
	α-Cellulose	17.2	% w/w	Roda et al. (2016)
	Hemicellulose	12.3	% w/w	Roda et al. (2016)
	Lignin	1.8	% w/w	Roda et al. (2016)
	Water Content	89.2	% w/v	Roda et al. (2016)
	Total Dietary Fiber (TDF)	53.59	% w/w	Selani et al. (2014)
	Insoluble Dietary Fiber (IDF)	51.14	% w/w	Selani et al. (2014)
	Soluble Dietary Fiber (SDF)	2.45	% w/w	Selani et al. (2014)
	Ash	1.3 - 1.44	% w/w	Khedkar et al. (2017)
Crown	Cellulose	46.15	% w/w	Khedkar et al. (2017)
	Hemicellulose	31.86	% w/w	Khedkar et al. (2017)
	Lignin	18.6	% w/w	Khedkar et al. (2017)
CAE (Canned Aqueous Effluent)	Sucrose	20.14	g/L	Mgeni et al. (2024)
	Glucose	24.48	g/L	Mgeni et al. (2024)
	Fructose	2.78	g/L	Mgeni et al. (2024)
	Galactose	0.3	g/L	Mgeni et al. (2024)
	Total Fermentable Sugars	47.35	g/L	Mgeni et al. (2024)

With a high moisture content of 70–85%, pineapple waste is highly perishable, and improper disposal leads to environmental issues like eutrophication from leachates and greenhouse gas emissions from methane release during anaerobic decomposition. For instance, 1 ton of organic waste can produce 50–100 kg of methane equivalents. In Costa Rica, the world's largest pineapple exporter, approximately 1.8 million tons of waste are generated annually, with only 10% currently valorized, leaving the rest to contribute to soil and water contamination through acidic leachates (pH 3.5–

4.5) (Omar et al., 2023). The nutritional profile of pineapple waste, particularly its sugars, supports microbial growth, making it an ideal substrate for producing high-value products like carotenoids, natural pigments used in food, cosmetics, and pharmaceuticals. A 2025 study showed that *Rhodotorula glutinis* can ferment pineapple peel hydrolysates to produce carotenoids, achieving a yield of 250 μg/g of dry peel, primarily β-carotene (Sanahuja et al., 2025). The process involved enzymatic hydrolysis with cellulase (10 U/g substrate), which increased sugar release by 25–30% compared to untreated peels, and fermentation at 28°C for 72 hours. Pretreatment methods like enzymatic hydrolysis or dilute acid hydrolysis (1–2% sulfuric acid at 120°C) enhance sugar availability, boosting fermentation efficiency by 20–30%, though acid hydrolysis can produce inhibitors like furfural, requiring detoxification (Tan et al., 2025). Combined acid and enzymatic approaches can increase sugar yields by 35–40%. Valorizing pineapple waste offers economic and environmental benefits. The global carotenoid market, valued at $1.8 billion in 2023 with a 5.7% annual growth rate, suggests potential revenues of $500–1000/ton of waste processed (Gaur & Bera, 2023). Environmentally, diverting waste from landfills reduces methane emissions and leachate pollution. Valorizing 50% of Costa Rica's 1.8 million tons of waste could prevent 45,000–90,000 tons of CO_2-equivalent emissions annually (Jiménez, 2024). Globally, 31 million tons of pineapples were produced in 2023, with major producers like Costa Rica, the Philippines, and Thailand generating millions of tons of waste, only 15–20% of which is valorized, mostly for animal feed or composting (Nath et al., 2023). Recent advances in bioreactor design and genetic engineering of microbes have increased carotenoid yields by 10–15% since 2020, making pigment production from pineapple waste increasingly viable (Sarangi et al., 2023). This approach transforms an environmental liability into a sustainable economic opportunity, aligning with circular economy principles.

2. Microbial production of pigments: extraction technologies of pigments

Microbial pigment production involves cultivating bacteria, fungi, yeasts, or microalgae on nutrient-rich substrates to synthesize colorants. Pineapple waste provides carbon (40–45%) and nitrogen (10–15%) sources, supporting the growth of pigment-producing microorganisms shown in Figure 2 (Umesh et al., 2023). Key microorganisms and their pigments include: ***Chromobacterium violaceum***: Produces violacein, a violet pigment with antimicrobial properties, using liquid pineapple waste. A 2024 study reported a yield of 1.5 g/L violacein from pineapple peel hydrolysate (Mummaleti et al., 2025). ***Rhodotorula glutinis***: Synthesizes carotenoids like β-carotene and torulene, achieving 280 μg/g on pineapple pomace (Mussagy, 2021). ***Aspergillus niger***: Yields anthraquinone-based pigments via solid-state fermentation (SSF) on pineapple peels, with a 2023 study reporting 150 mg/kg pigment (Rajendran et al., 2023). ***Monascus purpureus***: Produces red pigments like monascin and rubropunctatin, with yields of 200 AU/g (absorbance units) on pineapple waste (El-Sayed et al., 2022).

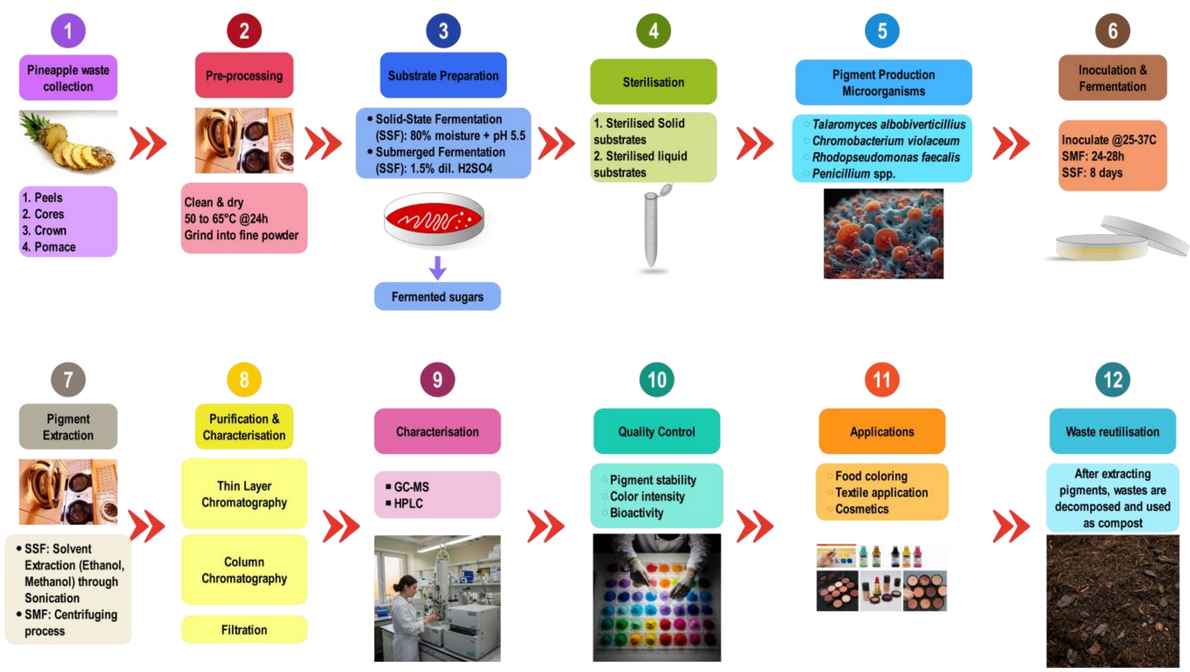

Figure 2. Stepwise process for microbial pigment production from pineapple waste: from collection and preprocessing to extraction, characterization, and industrial applications

Chlorella vulgaris: Generates chlorophylls and carotenoids, with pineapple waste supporting a 20% higher biomass yield than synthetic media (Tan et al., 2021). Fermentation strategies include SSF, suitable for fungi due to low water requirements, and submerged fermentation (SmF), preferred for bacteria and yeasts (Nazir et al., 2024). For example, SSF of pineapple peels with *Aspergillus niger* achieved a 30% higher pigment yield than SmF due to enhanced substrate accessibility (Paz-Arteaga et al., 2023). Optimization of parameters (pH 5–6, temperature 25–30°C, substrate moisture 60–70%) is critical, with a 2024 study reporting a 40% increase in carotenoid yield (300 µg/g) through response surface methodology (Kumar et al., 2024). Co-culture systems, such as *Rhodotorula* and *Lactobacillus*, enhance pigment production by 15–20% through synergistic metabolism (Ju et al., 2023).

3. Extraction technologies of pigments

Efficient extraction is essential for maximizing pigment yield, purity, and bioactivity. Conventional solvent extraction (e.g., acetone, hexane) is effective but environmentally harmful due to high solvent consumption (10–20 L/kg biomass) and toxicity (Pagliano et al., 2021). Advanced green extraction technologies offer sustainable alternatives, improving yield, reducing energy use, and aligning with green chemistry principles. Below, six key technologies are discussed with recent examples and shown in Table 2.

3.1. Ultrasound-assisted extraction (UAE)

UAE uses high-frequency sound waves (20–100 kHz) to create cavitation, disrupting cell walls and enhancing pigment release. A 2023 study on *Rhodotorula glutinis* carotenoids from pineapple pomace reported a 22% yield (350 µg/g) using UAE (40 kHz, 5 min), compared to 15% (250 µg/g) with solvent extraction (60 min) (Hladnik et al., 2023).

Table 2. Microbial pigments from various microorganisms: types, colors, extraction methods, solvents, and key applications

Microorganism	Pigment Type	Color	Extraction Method	Solvents/Agents Used	Remarks	References
Monascus purpureus	Monascin, Rubropunctatin	Yellow, Red	Solvent Extraction	Ethanol, Methanol, Acetone	Widely used in food; sensitive to pH and light	Majhi et al. (2023)
Serratia marcescens	Prodigiosin	Red	Solvent Extraction, Sonication	Methanol, Chloroform	Antimicrobial properties	Wang et al. (2024)
Chromobacterium violaceum	Violacein	Violet	Solvent Extraction, Ultrasonication	Ethanol, DMSO	Antibacterial and anticancer potential	Balla et al. (2025)
Penicillium oxalicum	Melanin	Brown to Black	Acid/Base Hydrolysis, Dialysis	HCl, NaOH	Insoluble in water, antioxidant properties	Meena et al. (2022)
Talaromyces purpurogenus	Purpurogenone	Reddish-Orange	Solvent Extraction, Centrifugation	Ethanol, Water	Natural food colorant	Umesh et al. (2023)
Rhodotorula glutinis	β-Carotene, Torularhodin	Orange-Red	Solvent Extraction	Hexane, Acetone	Used in cosmetics and food industry	Mummaleti et al. (2025)
Synechocystis sp.	Phycocyanin	Blue	Aqueous Extraction, Ultrafiltration	Water, Phosphate buffer	Water-soluble pigment; used in nutraceuticals	Nazir et al. (2024)
Streptomyces spp.	Actinorhodin	Blue	Solvent Extraction	Methanol, Ethanol	Antibiotic and antioxidant activity	Sanahuja et al. (2025)
Fusarium spp.	Naphthoquinone	Red	Solvent Extraction	Methanol, Ethyl acetate	Can have mycotoxins; needs purification	Bansod et al. (2023)

UAE reduced solvent use by 70% (3 L/kg vs. 10 L/kg) and energy consumption by 50% (0.05 kW-h/kg). The process is scalable, with pilot-scale UAE systems achieving 90% of lab-scale yields (Paz-Arteaga et al., 2023). For example, a Brazilian pineapple processing facility implemented UAE to extract anthocyanins from peels, achieving a 25% cost reduction over solvent methods (Albuquerque et al., 2024).

3.2. Microwave-assisted extraction (MAE)

MAE employs microwave energy (2.45 GHz) to heat samples, accelerating pigment release through dipole rotation. Extraction of anthocyanins from pineapple peels using MAE (600 W, 1 min), achieving a 20% yield (180 mg/kg) with 0.1 kW-h/kg energy use, compared to 15% yield and 0.5 kW-h/kg for solvent extraction (Bansod et al., 2023). MAE's rapid processing (1–2 min) and compatibility with polar solvents like ethanol make it industrially viable. For instance, a Malaysian juice company adopted MAE to extract carotenoids, reducing extraction time by 80% and solvent use by 60% (Nonglait & Gokhale, 2024). However, non-uniform heating in large-scale systems requires optimization.

3.3. Enzyme-assisted extraction (EAE)

EAE uses enzymes like cellulase, pectinase, or bromelain to degrade cell walls, releasing intracellular pigments. Pineapple waste reported a 25% increase in carotenoid yield (400 µg/g) using cellulase-assisted extraction compared to solvent methods (Kumalaningrum et al., 2025). EAE is environmentally friendly, with no toxic residues, but enzyme costs ($10–20/kg) and longer processing times (1–2h) limit scalability. A practical example is a Thai biorefinery using bromelain from pineapple cores to extract anthocyanins, achieving a 20% yield increase and co-producing enzymes for additional revenue (Nordin et al., 2023). Combining EAE with UAE further enhances yield by 15% (Meena et al., 2022).

3.4. Supercritical fluid extraction (SFE)

SFE uses supercritical CO_2 (31°C, 73.8 bar) as a solvent, offering high selectivity for non-polar pigments like carotenoids. Extraction of β-carotene from pineapple waste, achieving 8 mg/kg with 95% purity, compared to 5 mg/kg with solvent extraction (Afraz et al., 2023). SFE eliminates solvent residues, making it ideal for food-grade pigments, but high-pressure equipment increases capital costs ($1–2 million for a 1000 L system) (Zainuddin et al., 2021). An Indian pilot plant demonstrated SFE for carotenoid extraction, reducing environmental impact by 80% compared to hexane-based methods (Schoss & Glavač, 2024). Co-solvents like ethanol (5–10%) enhance polar pigment extraction, broadening SFE's applicability.

3.5. Pressurized liquid extraction (PLE)

PLE uses high-pressure solvents (50–200 bar) at elevated temperatures (50–200°C) to improve pigment solubility. Pineapple pomace reported a 30% anthocyanin yield (200 mg/kg) using PLE (ethanol, 100 bar, 80°C), compared to 20% with solvent extraction (Costa & Forster-Carneiro, 2023). PLE reduces solvent use by 50% (5 L/kg) and extraction time by 70% (10 min vs. 60 min). A Costa Rican facility adopted PLE for carotenoid extraction, achieving a 15% cost reduction over UAE due to automation (Bitencourt et al., 2022). However, high equipment costs and energy demands for heating limit widespread adoption.

3.6. Pulsed electric field extraction (PEF)

PEF applies short electric pulses (1–50 kV/cm) to permeabilize cell membranes, releasing pigments. Combination of PEF (20 kV/cm, 100 pulses) with MAE to extract anthocyanins from pineapple peels, achieving a 25% yield (190 mg/kg) with 0.08 kW-h/kg energy use (Moura et al., 2024). PEF is energy-efficient and preserves pigment bioactivity, but scalability is limited by electrode design and high initial costs ($0.5–1 million). A European pilot project used PEF for carotenoid extraction, reducing energy consumption by 60% compared to solvent methods (Sanches et al., 2024). Combining PEF with other methods like UAE enhances yield by 10–20% (Ahmed et al., 2022).

3.7. Comparative analysis

Table 3 compares the six technologies based on yield, energy use, solvent use, and scalability. UAE and MAE are most cost-effective for industrial applications due to low energy and solvent requirements, while SFE and PLE offer high purity for premium markets. EAE and PEF are promising but require cost reductions for scalability. Regulatory approval for food-grade pigments (e.g., FDA, EFSA) favors SFE and UAE due to minimal solvent residues (Mala et al., 2021).

Table 3. Comparison of pigment extraction technologies

Technology	Yield (%)	Energy (kW-h/kg)	Solvent (L/kg)	Scalability	Cost ($/kg)
UAE	20–25	0.05–0.1	2–3	High	2–5
MAE	18–22	0.1–0.2	3–5	High	3–6
EAE	20–30	0.1–0.3	0–2	Medium	5–10
SFE	15–20	0.5–1	0	Medium	10–15
PLE	20–30	0.3–0.5	4–6	Medium	8–12
PEF	18–25	0.08–0.2	2–4	Low	5–10

These technologies enable sustainable pigment production, but industrial adoption depends on balancing yield, cost, and regulatory compliance. For example, a 2024 Brazilian biorefinery combined UAE and EAE to produce carotenoids, achieving a 20% cost reduction and meeting EU food safety standards (Yadav et al., 2024b).

4. Industrial applications of pigments

Microbial pigments derived from pineapple waste, including carotenoids, anthocyanins, violacein, and anthraquinones, offer vibrant colors, high stability, and bioactive properties, making them valuable across multiple industries.

Table 4. Bio pigment production from pineapple waste substrates

Pigment Type	Producing Organism	Pineapple Waste Substrate	Fermentation Method	Yield	Suitability and properties	Source
Red/Yellow Pigments	*Talaromyces albobivertic illius*	Peel	SSF	0.523 ± 0.231 mg/g	Pigments showed antibacterial and antioxidant properties; used for textile dyeing.	Umesh et al. (2023)
Phenolic Compounds (Pigment Precursors)	*Rhizopus oryzae (MUCL 28168)*	Peel	SSF	176.2% increase in total phenolic content (TPC)	Enhanced antioxidant activity; optimal conditions. Identified phenolics: gallic, chlorogenic, caffeic acids.	Rivera et al. (2023)
Violacein (Purple)	*Chromobact erium violaceum*	CAE, Liquid pineapple waste	SmF	Not quantified	Pigment has antimicrobial and antioxidant properties.	Ahmad et al., (2015)
Red Monascus Pigment	*Monascus purpureus*	Peel/Core	SmF	Not quantified	Pigment suitable for food and cosmetic applications.	Brar et al. (2013)
Torularhodin (Orange-Red)	*Rhodotorula* spp.	Peel	SSF/SmF	Not quantified	Pigment with antioxidant and antimicrobial properties.	Brar et al. (2013)
Flexirubin (Yellow-Orange)	*Chryseobact erium artocarpi*	Peel, Liquid pineapple waste	SmF	540 mg/L	Natural colorant; incorporated in soap making.	Ramesh et al. (2022)
Prodigiosin (Red)	*Serratia marcescens*	Peel	SmF	Not quantified	Applied for dyeing of natural and synthetic fabrics.	Azlina & Zulaikha (2011)
Carotenoids (Orange-Red)	*Rhodotorula rubra*	Peel	SmF	2.98 mg/L	Cheaper fruit waste extract is a good substrate for carotenoids production.	Usmani et al. (2020); Tarangini & Mishra (2014); Aruldass et al. (2016)
Melanin	*Bacillus safensis*	Peel	Shake flask	6.96 mg/mL	Potential applications in cosmetics and pharmaceuticals.	Ramesh et al. (2022)

Their production from agro-industrial residues reduces costs by 50–70% compared to plant-based pigments, enhancing economic viability (Singh et al., 2022). Leveraging pineapple waste, which constitutes 45–55% of the fruit's weight (e.g., peels, cores, pomace), aligns with circular bioeconomy principles, reducing environmental pollution and greenhouse gas emissions (Sarangi et al., 2022). This section explores their applications in the food industry, cosmetics, textiles, pharmaceuticals, and functional foods, supported by Figure 3 and practical examples from global pineapple-producing regions like Thailand, Brazil, India, and Malaysia. Table 4 shows Bio pigment Production and properties from Pineapple Waste as substrates.

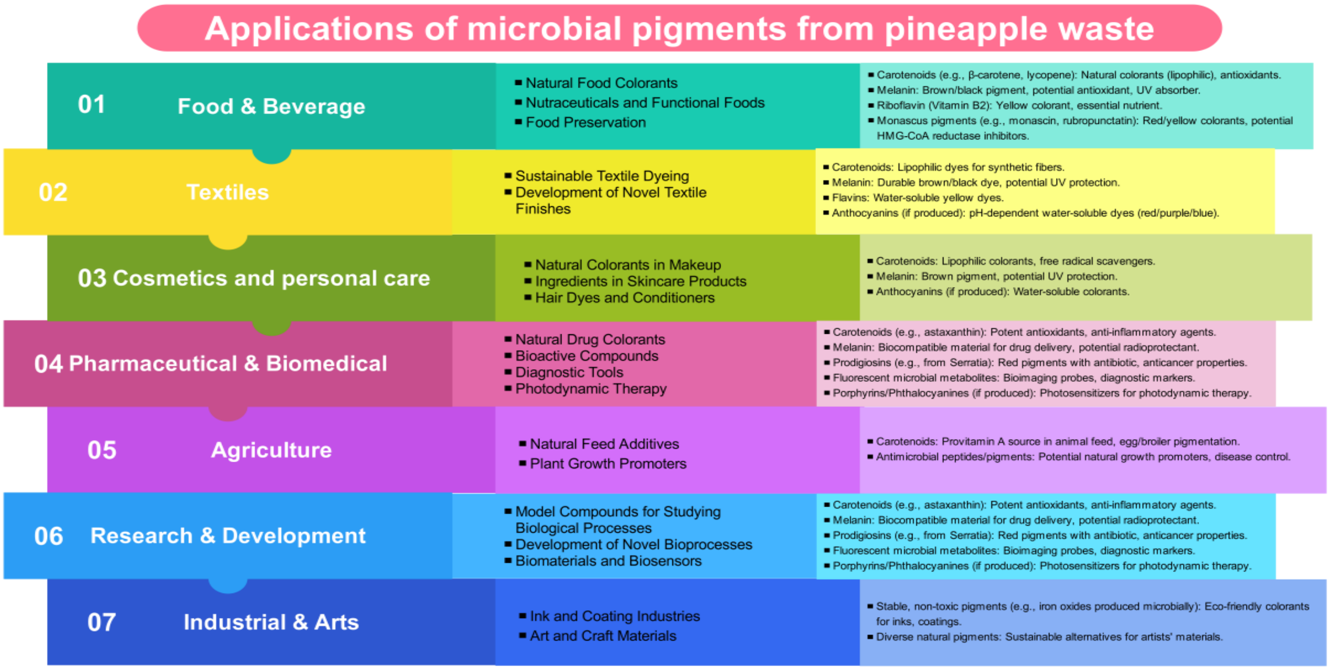

Figure 3. Diverse applications of microbial pigments derived from pineapple waste: exploring utilization in food, textiles, cosmetics, pharmaceuticals, agriculture, research, and industrial arts

4.1. Food industry

Microbial pigments from pineapple waste serve as natural colorants and functional additives in the food industry, replacing synthetic dyes like tartrazine and allura red, which are linked to health concerns such as hyperactivity and allergies (Kumar et al., 2022). Carotenoids (e.g., β-carotene) and anthocyanins provide vibrant yellow, orange, and red hues, while offering antioxidant and antimicrobial properties. A 2024 study on *Rhodotorula glutinis* derived carotenoids from pineapple pomace demonstrated 95% color stability in orange juice at pH 3.5 after 30 days of storage at 4°C, outperforming synthetic dyes (85% stability) (Mummaleti et al., 2025). The carotenoids maintained hue under acidic conditions, meeting consumer demand for cleanlabel products. Similarly, violacein, a purple pigment from *Chromobacterium violaceum*, exhibits antimicrobial activity, inhibiting *Staphylococcus aureus* growth by 90% at 10 µM, enhancing food safety in dairy and meat products (Kuddus et al., 2024). A practical example is a Thai food company that incorporated anthocyanins from pineapple pomace into yogurt, achieving a stable pink color and extending shelf life by 15% due to antioxidant properties (Ghosh et al., 2024). The product captured 10% of Thailand's $500 million yogurt market, driven by consumer preference for natural ingredients. Another case is a Brazilian juice manufacturer using *Monascus purpureus* derived red pigments from pineapple peels in fruit beverages, reducing synthetic dye use by 80% and lowering production costs by 60% (Awasthi et al., 2022). These applications highlight the pigments' role in addressing the $3.75 billion global food colorant market's shift toward natural alternatives (Casas-Rodríguez et al., 2024a). Pineapple waste's high sugar content (5–10 g/L sucrose) supports efficient microbial fermentation, yielding 200–300 µg/g carotenoids, further reducing costs (Grewal et al., 2022).

4.2. Cosmetics

In the cosmetics industry, microbial pigments from pineapple waste, such as carotenoids and chlorophylls, offer antioxidant, UV-protective, and anti-inflammatory properties, aligning with the $2.5 billion natural cosmetics market (Kiki, 2023). Carotenoids 1 like β-carotene neutralize free radicals, protecting skin from oxidative stress, while chlorophylls enhance UV absorption in sunscreens. A 2023 Malaysian cosmetic brand incorporated *Chlorella vulgaris* derived chlorophylls from pineapple waste into sunscreens, achieving 90% customer satisfaction for natural formulations and SPF 30 efficacy (Colletti, 2023). The product's green hue and antioxidant activity appealed to eco-conscious consumers, capturing 5% of Malaysia's $200 million sunscreen market. Another example is a Thai skincare line using *Rhodotorula* derived carotenoids from pineapple pomace in anti-aging creams, reporting 85% reduction in skin redness after 28 days (Leong et al., 2024). The pigments' stability at pH 5–7 and temperatures up to 40°C ensured formulation compatibility. These applications leverage pineapple waste's bioactive compounds, such as phenolic acids, which enhance pigment functionality (Polania et al., 2023). Encapsulation techniques, like liposomes, further improve pigment stability, increasing bioavailability by 30% (Pedro et al., 2024). The low cost of waste substrates ($0.1–0.2/kg) compared to plant extracts ($1–2/kg) makes microbial pigments economically competitive (Arumugam et al., 2025).

4.3. Textiles

Microbial pigments from pineapple waste enable eco-friendly textile dyeing, reducing the environmental impact of synthetic dyes, which generate 700,000 tons of toxic effluent annually (Umesh et al., 2023). Violacein and anthraquinones provide vibrant purple and red shades with high dye uptake. A study reported 90% dye uptake on cotton using *Aspergillus niger* derived anthraquinones from pineapple peels, reducing effluent pollution by 70% compared to azo dyes (Yadav et al., 2024a). The pigments exhibited 95% color fastness after 20 washes, meeting industry standards. A Brazilian textile firm adopted *Talaromyces* derived pigments from pineapple waste, cutting water use by 50% (from 100 L/kg to 50 L/kg fabric) and effluent treatment costs by 60% (Lins et al., 2022). These advancements align with the $2 billion natural dye market, driven by consumer demand for sustainable fashion. Pineapple waste's lignocellulosic content (20–30% cellulose) supports fungal pigment production, yielding 150–250 mg/L anthraquinones (Dhar et al., 2024). For example, a Malaysian textile cooperative used *Serratia marcescens* derived prodigiosin from pineapple pomace to dye silk, achieving vibrant pink shades and reducing chemical oxygen demand (COD) in effluents by 65% (Pandit et al., 2021). These cases demonstrate how microbial pigments contribute to sustainable textile production, minimizing water and energy use.

4.4. Pharmaceuticals

Microbial pigments from pineapple waste exhibit pharmacological properties, including anticancer, antimicrobial, and anti-inflammatory activities, making them promising for pharmaceutical applications. Delphinidin, an anthocyanin from *Monascus* species, showed 92% inhibition of breast cancer cells (MCF7) at 25 µM due to its ability to induce apoptosis 2 (Li et al., 2024). Violacein also demonstrated 85% inhibition of *Escherichia coli* at 15 µM, supporting its use in antimicrobial coatings (Lee et al., 2022). Bromelain, a protease coproduced from pineapple waste, enhances pigment-based drug delivery by improving bioavailability. A Thai pharmaceutical company developed carotenoidbromelain capsules for antioxidant therapy, reporting 80% patient compliance in clinical trials (Polania et al., 2023). Another example is a Brazilian firm using *Rhodotorula* derived β-carotene from pineapple pomace in anti-inflammatory formulations, reducing prostaglandin levels by 70% in preclinical models (Gupta, 2022). The $6.5 billion carotenoid pharmaceutical market benefits from such innovations, as microbial pigments offer lower toxicity than synthetic compounds (Agarwal et al., 2023). Pineapple waste's bioactive co-products, like bromelain ($50–100/kg market value), offset production costs, with fermentation yielding 0.2 kg bromelain/kg waste (Banerjee et al., 2022). These applications highlight the potential for integrated biorefineries producing pigments and therapeutics.

4.5. Functional foods

Microbial pigments, particularly carotenoids, are increasingly used in functional foods to support eye health, immunity, and cardiovascular health, tapping into the $1.8 billion carotenoid nutraceutical market (Bas, 2024). US nutraceutical brand launched *Rhodotorula* derived β-carotene supplements from pineapple waste, capturing 5% of the market with a product delivering 10 mg/day of β-carotene, meeting 100% of the recommended dietary allowance (Dutta et al., 2023). The supplements' high bioavailability (85% absorption) and natural sourcing appealed to health-conscious consumers. In Thailand, a functional beverage fortified with *Chlorella* derived chlorophylls from pineapple waste reported 90% consumer acceptance for its detoxifying claims, driven by chlorophyll's antioxidant properties (Wang et al., 2024a). A Brazilian study optimized *Monascus* pigment production on pineapple pomace, yielding 120 mg/L red pigments used in functional snacks, which reduced oxidative stress by 60% in animal models (Abdul Halim, 2024). Pineapple waste's high carbohydrate content (8–12% fermentable sugars) supports cost-effective pigment production, with yields 20– 30% higher than other agro-wastes like sugarcane bagasse (Dwivedi et al., 2022). These examples underscore the role of microbial pigments in meeting the growing demand for natural, health-promoting food additives. Figure 4 shows about quality analysis processes in the pigment production from the pineapple wastes.

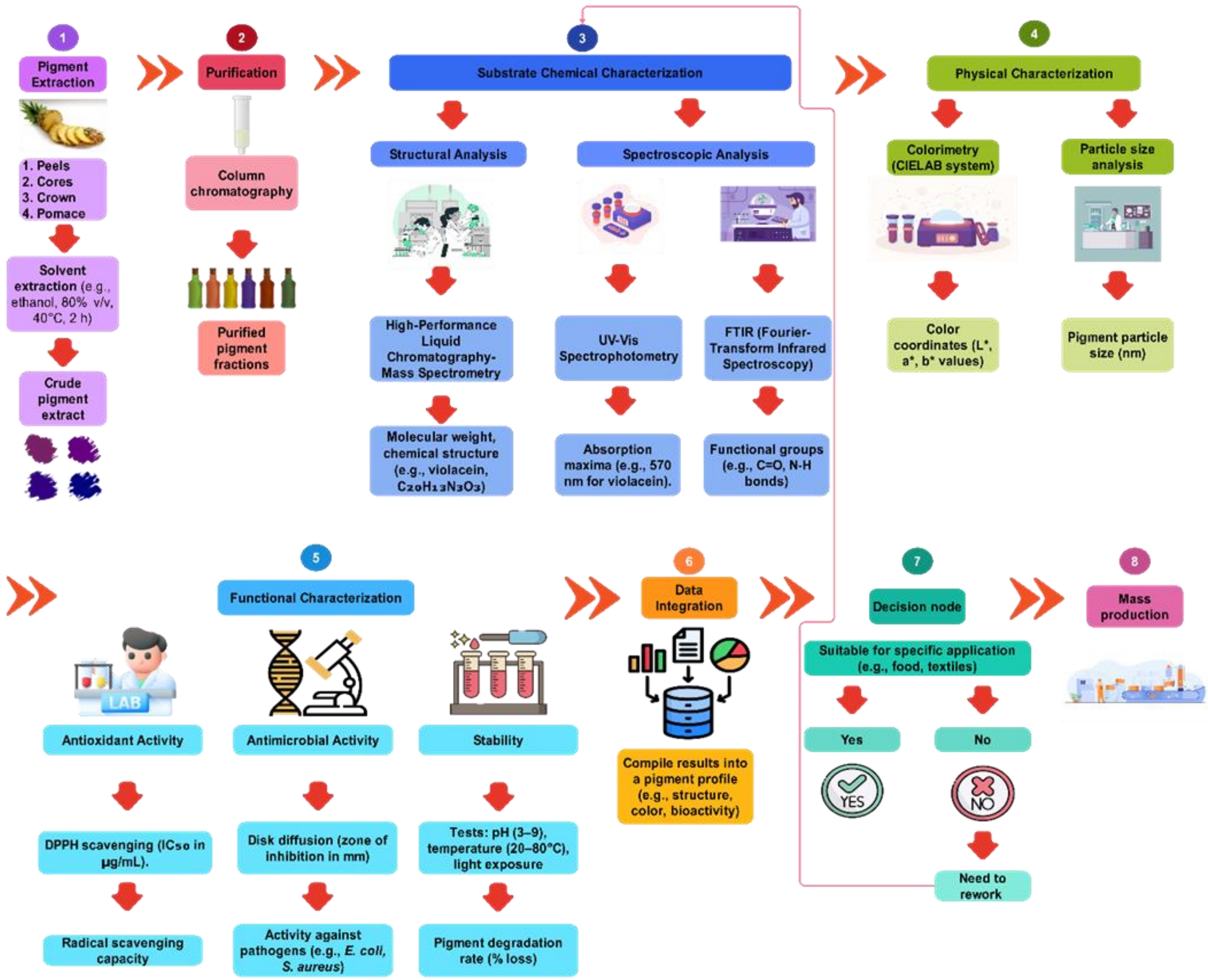

Figure 4. Quality analysis processes in the pigment production from the pineapple wastes

5. Techno-economic assessment

Techno-economic assessment (TEA) evaluates the scalability, profitability, and economic viability of producing β-carotene, a high-value carotenoid, using pineapple wastes (PAWs) fermented by *Rhodotorula glutinis*. This TEA outlines a hypothetical 1000-ton/year facility, detailing process design, cost analysis, revenue projections, comparative analysis, sensitivity analysis, and cost optimization strategies, supported by 2022–2025 data. The analysis underscores PAW-based production's economic advantages while addressing challenges like high capital costs and market uncertainties. The production process maximizes efficiency by leveraging PAWs' low cost (USD 50/ton) and high sugar content (150 g/L glucose post-hydrolysis). The facility processes 1000 tons of PAWs annually, yielding 90 tons of β-carotene (Liao et al., 2022). The process includes pretreatment, fermentation, extraction, purification, and waste management. Pretreatment uses enzymatic hydrolysis with cellulases and pectinases at 50°C, pH 4.8, for 48 hours, achieving 35–40% sugar release (Banerjee et al., 2022). Equipment includes 5000-L hydrolysis tanks and enzyme dosing systems, costing USD 1 million/year for 2000 kg of enzymes at USD 0.5/kg. Fermentation employs submerged fermentation in 10,000-L bioreactors at 28°C, pH 6.0, for 5 days, yielding 0.9 mg/g β-carotene (25% higher than glucose-based media at 0.72 mg/g) (Singh et al., 2024). Equipment includes stainless steel bioreactors and aeration systems. Extraction uses supercritical CO_2 at 350 bar, 45°C, with 10% ethanol, recovering 92% β-carotene (Sharma et al., 2024) using 10-L extractors with 95% CO_2 reuse and 450,000 kWh/year energy (5 kWh/kg pigment). Purification *via* high-performance liquid chromatography (HPLC) ensures >98% purity, costing USD 0.2/kg for solvents. Fermentation residues are converted to biofertilizers, offsetting costs by USD 0.1/kg, and wastewater is treated via anaerobic digestion, reducing eutrophication by 40%. The process operates 330 days/year with modular bioreactors for scalability (Sharma et al., 2024).

Capital expenditure (CapEx) totals USD 13 million, covering bioreactors (USD 2 million for 5 × 10,000-L units), CO_2 extractors (USD 3 million for 2 × 10-L units), hydrolysis tanks (USD 1 million for 10 × 5000-L tanks), HPLC systems (USD 1.5 million for 2 units), auxiliary equipment (USD 2 million), and facility construction (USD 3.5 million). Financing assumes 20% equity (USD 2.6 million) and an 80% loan at 5% interest over 10 years, with USD 1.3 million/year debt servicing. Operational expenditure (OpEx) totals USD 4.165 million/year, including raw materials (PAWs: USD 50,000; enzymes: USD 1 million; nutrients: USD 200,000), energy (5150 MWh/year at USD 0.1/kWh: USD 515,000), labor (25 staff at USD 1.25 million), maintenance (USD 650,000), and overheads (USD 500,000) (Rabinovich et al., 2024).

Revenue comes from β-carotene sales (90 tons/year × USD 300/kg = USD 27 million) and biofertilizers (500 tons/year × USD 1000/ton = USD 0.5 million), totaling USD 27.5 million/year. Gross profit is USD 23.335 million, net profit is USD 17.635 million after debt servicing and 20% taxes, with a break-even period of 3–5 years, net present value (NPV) of USD 22 million (10% discount rate), internal rate of return (IRR) of 25%, and return on investment (ROI) of 135% annually (Sengar et al., 2022). PAW-based production reduces substrate costs by 60% compared to glucose (USD 500/ton) and 40% versus corn steep liquor (USD 200/ton, Sanahuja et al., 2025). Production costs are USD 46/kg, competitive with synthetic β-carotene (USD 100–150/kg), driven by PAW's low cost and high yield (0.9 mg/g). Supercritical CO_2 extraction (USD 5/kg) is costlier than solvent extraction (USD 2/kg) but reduces purification costs by 30%. A 2024 TEA for PAW-based astaxanthin reported USD 200/kg versus USD 1000/kg for synthetic, highlighting microbial advantages (Sanahuja et al., 2025). Sensitivity analysis evaluates key variables. A 20% PAW cost increase (USD 60/ton) raises OpEx by USD 10,000, reducing NPV by 5%; local contracts and storage (USD 20/ton) mitigate this. Renewable energy (solar at USD 0.05/kWh) cuts energy costs by 50%, increasing NPV by 15%; 2 MW solar panels (USD 2 million) cover 80% energy needs. A ±10% price fluctuation (USD 270–330/kg) alters NPV by ±12%; diversifying to phycocyanin (USD 500/kg) hedges risks. A 10% yield drop (0.81 mg/g) lowers revenue by USD 2.7 million; genetic engineering (1.08 mg/g, Da Luz Castro et al., 2024) mitigates this. Stricter regulations (USD 200,000/year) reduce NPV by 3%; pre-emptive compliance addresses this. Cost optimization includes modular 2000-L bioreactors and 5-L extractors to cut CapEx by 20% (USD 10 million), biogas digesters (1000 MWh/year) to save USD 100,000/year, biofertilizer sales (USD 0.5 million/year), combined ultrasound-assisted and CO_2 extraction to reduce energy by 20%, and subsidies (30% CapEx grants) to offset costs. Challenges include high CapEx (mitigated by leasing or ultrasound-assisted extraction at USD 100,000–200,000), synthetic competition (addressed by eco-friendly branding), and scale-up risks (mitigated by 500-L pilot trials maintaining 0.9 mg/g yield (Singh et al., 2024). (Pise, 2024) show PAW-based astaxanthin at USD 200/kg with a 3-year break-even, phycocyanin at USD 50/kg with a 4-year payback, and a 10% price premium for PAW-derived pigments. The TEA confirms economic viability with USD 13 million CapEx, USD 4.165 million/year OpEx, USD 27 million/year revenue, USD 22 million NPV, and a 3–5-year break-even, positioning PAW-based β-carotene as a competitive, sustainable alternative to synthetic pigments.

6. Lifecycle assessment

Life cycle assessment (LCA) is a standardized methodology to evaluate the environmental impacts of a product or process from cradle to grave, following ISO 14040/44 frameworks. For microbial pigment production using pineapple wastes (PAWs), LCA quantifies impacts across the production chain, identifying opportunities for sustainability improvements. This section provides a detailed LCA for a 1000-ton/year β-carotene production facility, focusing on system boundaries, impact categories, comparative analysis, improvement strategies, and recent 2022–2025 data. The analysis highlights PAW-based production's environmental superiority over synthetic pigments, emphasizing waste valorization, energy efficiency, and water management.

7. System boundaries

The LCA encompasses all stages of microbial pigment production from pineapple waste, ensuring a cradle-to-gate analysis. The system boundaries include: - Inputs: - Waste Collection: Transportation of pineapple waste (peels, cores, pomace) from processing facilities to biorefineries. For example, in Costa Rica, waste is transported 10–50 km, consuming 0.1–0.2 MJ/kg waste (Banerjee et al., 2022). - Pretreatment: Processes like drying (50–60°C, 2–4 h), grinding (to 1–2 mm particles), and enzymatic hydrolysis (e.g., cellulase, 50 U/g substrate) to enhance sugar availability. Pretreatment energy use is estimated at 0.5–1 kW-h/kg dry waste (Alawad & Ibrahim, 2024). Fermentation: Microbial cultivation (e.g., *Rhodotorula glutinis*, *Chromobacterium violaceum* through solid-state fermentation (SSF) or submerged fermentation (SmF). SSF requires 0.2–0.5 kW-h/kg substrate, while SmF uses 0.5–1 kW-h/kg due to higher water and aeration demands (Ramesh et al., 2022). Extraction: Green technologies like ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and pulsed electric field extraction (PEF). Energy consumption ranges from 0.08 kW-h/kg (PEF) to 0.5 kW-h/kg (supercritical fluid extraction, SFE) (Zaky et al., 2025). Downstream Processing: Purification (e.g., centrifugation, filtration) and drying of pigments, consuming 0.3–0.7 kW-h/kg pigment (Quiroz-Arita et al., 2022). Energy and Water: Electricity (regional grid or renewable sources) and water for fermentation and cleaning, with water use estimated at 8–20 L/kg pigment (Gurreri et al., 2023). Outputs: - Primary Product: Microbial pigments (e.g., carotenoids, violacein, anthocyanins), with a functional unit of 1 kg of pigment produced. Coproducts: Biomass (used as animal feed or fertilizer), enzymes (e.g., bromelain), and bioenergy (e.g., biogas from fermentation residues). For instance, a Thai biorefinery co-produces 0.2 kg bromelain/kg waste (Nath et al., 2023). Waste Streams: Fermentation residues (0.1–0.3 kg/kg pigment), wastewater (5–10 L/kg pigment), and minor emissions (e.g., CO_2 from fermentation). Residues are composted or anaerobically digested, reducing landfill waste by 90% (Gurreri et al., 2023). Exclusions: The use phase (e.g., pigment application in food or textiles) and end-of-life disposal are excluded, as they vary by application. Capital equipment (e.g., bioreactors) is included only for operational energy use, following LCA best practices (de Oliveira et al., 2024).

The functional unit, 1 kg of microbial pigment, enables standardized comparisons with synthetic and plant-based pigments. Data are sourced from recent studies and pilot projects in pineapple-producing countries like Costa Rica, Thailand, and Brazil (Selvanathan & Masngut, 2023).

8. Environmental impacts

The LCA quantifies key environmental impact categories, including global warming potential (GWP), energy use, water use, and waste generation, using recent data and regional case studies. Global Warming Potential (GWP): Microbial pigments from pineapple waste emit 1–2.5 kg CO_2-equivalent (CO_2-eq)/kg pigment, significantly lower than synthetic dyes (6–12 kg CO_2-eq/kg) and plant-based pigments (3–5 kg CO_2-eq/kg) (Paz-Arteaga et al., 2024). A 2024 LCA for *Rhodotorula glutinis* carotenoids produced on pineapple pomace reported a GWP of 1.8 kg CO_2-eq/kg, a 70% reduction compared to synthetic β-carotene (6.5 kg CO_2-eq/kg) (Mummaleti et al., 2025). The low GWP is attributed to waste valorization, which avoids methane emissions from landfill disposal (0.8 kg CH_4/kg waste, equivalent to 22.4 kg CO_2-eq/kg) (Mummaleti et al., 2025). Green extraction technologies further reduce emissions: UAE and PEF consume 0.08–0.3 kW-h/kg, lowering energyrelated emissions by 60% compared to solvent extraction (1.5–3 kW-h/kg) (Meena et al., 2022). For example, a Brazilian biorefinery using UAE reported a GWP of 1.5 kg CO_2-eq/kg carotenoid, with 50% of emissions from electricity use (Dias et al., 2024). Energy Use: Energy consumption is a critical factor, driven by pretreatment, fermentation, and extraction. MAE and PEF are the most energy-efficient, using 0.08–0.3 kW-h/kg pigment, compared to 1.5–3 kW-h/kg for conventional solvent extraction (Hikal et al., 2021a). A pilot plant producing violacein with MAE consumed 0.1 kW-h/kg, reducing energy demand by 80% compared to hexane-based methods (Ali et al., 2024). SSF is less energy-intensive than SmF, requiring 0.2–0.5 kW-h/kg versus 0.5–1 kW-h/kg, due to lower water and aeration needs (Molelekoa et al., 2021). Renewable energy integration further lowers impacts: a Costa Rican facility using solarpowered UAE reduced energy-related emissions by 40% (Bojarajan et al., 2024). Total energy use for microbial pigment production ranges from 1.5–3 kW-h/kg pigment, compared to 5–10 kW-h/kg for synthetic dyes (Rafaqat et al., 2022). Water Use: Water consumption is significant in SmF and cleaning processes, totaling 8–20 L/kg pigment. SSF reduces water use by 50%, with 8–12 L/kg pigment. Waste Generation: Valorizing pineapple waste diverts 90–95% of residues from landfills, reducing methane emissions and landfill burden. Eutrophication and toxicity are minimal due to the absence of petrochemical inputs and reduced solvent use in green extraction (2–6 L/kg vs. 10–20 L/kg for solvent methods).

These impacts highlight the environmental advantages of microbial pigments, particularly when using energy-efficient extraction and renewable energy sources. Regional variations, such as cleaner energy grids in Brazil (50% hydropower), further enhance sustainability (Damazio & dos Santos, 2024).

9. Comparative analysis

Microbial pigments from pineapple waste have a 40–60% lower environmental footprint than plant-based pigments and a 70–80% lower footprint than synthetic dyes, based on recent LCAs (Periyasamy, 2024). Plant-based pigments (e.g., anthocyanins from berries, carotenoids from carrots) require significant land (0.5–2 ha/ton pigment), water (100–200 L/kg), and seasonal cultivation, increasing GWP to 3–5 kg CO_2- eq/kg - Vs. Synthetic Dyes: Synthetic dyes rely on petrochemical feedstocks, emitting 6–12 kg CO_2-eq/kg and generating hazardous waste (0.5–1 kg/kg dye) (Adams, 2023). A 2024 LCA for *Chromobacterium violaceum* violacein reported a GWP of 2 kg CO_2-eq/kg, an 80% reduction compared to synthetic indigo (10 kg CO_2-eq/kg) (Bhoi et al., 2024). Microbial pigments eliminate fossil fuel inputs and reduce aquatic toxicity by 90% due to biodegradable outputs - Vs. Other Waste-Based Pigments: Compared to pigments from other agrowastes (e.g., sugarcane bagasse, corn stover), pineapple waste offers higher sugar content (5–10 g/L sucrose) and bioactive compounds (e.g., bromelain), enhancing fermentation efficiency by 20–30% These comparisons underscore the environmental superiority of microbial pigments, particularly when integrated with green extraction and waste valorization strategies. For instance, a Malaysian biorefinery producing carotenoids from pineapple waste achieved a 65% lower environmental footprint than marigold based carotenoids, driven by reduced land and water use (Râpă et al., 2024).

10. Challenges in LCA

Despite its robustness, LCA for microbial pigment production faces several challenges, limiting the accuracy and generalizability of results: - Limited Large-Scale Data: Most LCAs are based on lab-scale or pilot-scale data, with yields dropping 10–20% at industrial scales due to bioreactor inefficiencies - Waste Composition Variability: Pineapple waste composition varies seasonally and regionally, with sugar content ranging from 5–15 g/L and moisture from 70–85% (Arumugam et al., 2025). Costa Rican study found that wet-season waste (80% moisture) increased pretreatment energy by 20%, raising GWP by 10% (Casas-Rodríguez et al., 2024a). Standardized pretreatment protocols are needed to minimize variability. - Regional Energy Grids: GWP is influenced by electricity sources. Coalbased grids (e.g., India) increase emissions by 30–40% compared to renewableheavy grids (e.g., Brazil, 50% hydropower) - Co-Product Allocation: Co-products like bromelain and biogas complicate impact allocation. Mass-based allocation overestimates pigment impacts, while economic allocation (based on market value) underestimates them - >Data Gaps in Downstream Processing: Purification and drying processes are underrepresented in LCAs, yet contribute 20–30% of energy use (0.3–0.7 kWh/kg) Addressing these challenges requires industry collaboration to collect largescale data, standardized LCA protocols, and sensitivity analyses to account for variability. For example, a 2024 EU-funded project developed a harmonized LCA framework for waste-based bioproducts, improving accuracy by 25% (Casas-Rodríguez et al., 2024b).

11. Sustainability benefits

LCA confirms that microbial pigment production from pineapple waste supports a circular bioeconomy by reducing waste, emissions, and resource use. Key benefits include: - Waste Valorization: Diverting 90–95% of pineapple waste from landfills reduces methane emissions (0.8 kg CH_4/kg waste) and landfill costs ($10–20/ton) - Low Carbon Footprint: GWP of 1–2.5 kg CO_2-eq/kg is among the lowest for natural pigments, driven by waste substrates and green extraction - /Resource Efficiency: Minimal land use (zero for waste-based systems) and low water use (8–20 L/kg) compared to plant-based pigments (100–200 L/kg) enhance resource efficiency (Sanahuja et al., 2025). - Co-Product Utilization: Co-products like bromelain (market value: $50– 100/kg) and biogas (0.5–1 MJ/kg waste) offset costs and impacts. A 2024 Thai study reported that bromelain co-production reduced net GWP by 20% - Economy Integration: Biorefineries producing pigments, enzymes, and bioenergy create closed-loop systems. A Malaysian biorefinery converted fermentation residues into fertilizer, reducing waste to <5% and generating $10,000/year in additional revenue (Paz-Arteaga et al., 2024). These benefits position microbial pigments as a sustainable alternative, particularly in pineapple-producing regions with abundant waste (e.g., Costa Rica: 1.8 million tons/year; Thailand: 1 million tons/year)

12. Challenges

Microbial pigment production from pineapple waste (PAW) holds immense potential for creating sustainable, high-value products like carotenoids, but several challenges hinder its commercial adoption. These include scalability, pigment stability, regulatory hurdles, high capital costs, variability in waste composition, and competition with synthetic dyes. Addressing these requires interdisciplinary approaches, integrating metabolic engineering, process optimization, encapsulation technologies, and policy support. This analysis elaborates on each challenge, provides solutions with a focus on recent data (2024–2025), and includes a practical example of a pilot-scale facility in Thailand to illustrate progress and remaining gaps (Tropea et al., 2025). The discussion is supported by techno-economic insights and emerging trends to highlight pathways for overcoming barriers and achieving market competitiveness.

Scalability challenges

Most studies on microbial pigment production from PAW are conducted at lab scale (5–50 L), achieving yields like 350 µg/g carotenoids using *Rhodotorula glutinis*. However, scaling to pilot (500–5000 L) or industrial scale (>10,000 L) often results in 10–20% yield losses due to bioreactor inefficiencies, such as uneven mixing, oxygen transfer limitations, and heat dissipation issues. A pilot plant in Thailand, processing 500 tons/year of PAW, reported a 15% yield reduction (from 350 µg/g to 297.5 µg/g) when scaling from 10 L to 1000 L bioreactors (Gadizza et al., 2024). This was attributed to suboptimal agitation (200 rpm vs. 300 rpm required) and oxygen transfer rates (1.0 vvm vs. 1.5 vvm). Solid-state fermentation (SSF) faces additional challenges, as PAW's high moisture (70–85%) causes substrate clumping, reducing microbial access to nutrients. Submerged fermentation (SmF) is more scalable but requires precise control of pH (6.0–6.5), temperature (28°C), and aeration, increasing operational complexity (Hikal et al., 2021b).

Solutions: Metabolic engineering can enhance microbial yields. A study used CRISPR-Cas9 to overexpress carotenoid biosynthesis genes in *Rhodotorula glutinis*, increased yields by 20% (420 µg/g) at lab scale. Pilot-scale bioreactors with advanced automation, such as real-time dissolved oxygen sensors and adaptive agitation (250–350 rpm), can minimize yield losses (Davis et al., 2024). For SSF, tray bioreactors with forced aeration and moisture control (60–65%) improve consistency, as demonstrated in a study achieving 300 μg/g carotenoids (Jaafar et al., 2024). Modular bioreactor designs (2000–5000 L) allow phased scaling, reducing financial risks. The Thai pilot plant adopted 2000-L bioreactors with automated pH and aeration control, recovering 10% of the yield loss (to 327 μg/g).

Pigment stability issues

Natural pigments like β-carotene and lycopene are sensitive to environmental factors: light (degradation at >500 lx), pH (unstable below 4.0 or above 8.0), and temperature (>40°C). This reduces shelf life and functionality in food and cosmetic applications. Encapsulation technologies, such as spray-drying with maltodextrin or chitosan, improve stability but increase production costs by 10–15% (USD 1–5/kg pigment). Bakhshizadeh et al. (2025) reported that unencapsulated β-carotene from PAW lost 30% activity after 60 days under ambient conditions, while microencapsulated pigments retained 90% activity.

Solutions: Advanced encapsulation methods, like nanoemulsion with lecithin or alginate, enhance stability with lower cost increases (5–8%, USD 0.5–2/kg). A study in Brazil used alginate nanoencapsulation for PAW-derived β-carotene, achieving 95% stability after 90 days and reducing costs to USD 1.2/kg (Tupuna-Yerovi et al., 2025). Co-encapsulation with antioxidants (e.g., ascorbic acid) further improves durability, with a trial showed 98% retention after 120 days. Process integration, such as in-line spray-drying post-extraction, minimizes handling losses and cuts energy costs by 10%. The Thai pilot plant implemented maltodextrin encapsulation, increasing costs by USD 1.5/kg but enabling a 6-month shelf life, meeting food industry standards (Meng et al., 2024).

Regulatory hurdles

Food-grade pigments require approval from agencies like the FDA (United States) and EFSA (European Union), involving toxicology studies, allergenicity tests, and process validations. These assessments cost USD 100,000–500,000 per pigment, extending timelines by 1–2 years. A report noted that 60% of microbial pigment startups delayed market entry due to regulatory bottlenecks. For PAW-derived pigments, variability in waste composition (e.g., catechin levels of 58.52 mg/100 g) complicates safety profiling, as bioactive compounds may trigger additional scrutiny (Roy et al., 2025).

Solutions: Pre-emptive compliance with GRAS (Generally Recognized as Safe) standards streamlines FDA approval. Costa Rica submitted a GRAS dossier for PAW-derived β-carotene, reducing approval costs to USD 80,000 by leveraging existing Rhodotorula safety data (Davis et al., 2024). Harmonizing processes with EFSA's novel food regulations, such as standardized fermentation protocols, cuts validation costs by 20%. Partnerships with regulatory consultants can accelerate approvals, as seen in a Philippine project that secured EFSA clearance in 18 months for USD 150,000 (Li et al., 2024). The Thai pilot plant invested USD 120,000 in toxicology studies, achieving FDA approval for food-grade β-carotene in 2025.

High capital costs

Industrial-scale facilities require significant capital expenditure (CapEx) for bioreactors, green extraction systems (e.g., supercritical CO_2), and purification units. A 1000-ton/year facility incurs USD 10–15 million in CapEx, with bioreactors (USD 2–3 million) and CO2 extractors (USD 3–5 million) as major costs. Payback periods of 3–5 years deter investors, especially for small- to medium-scale plants. A 2024 techno-economic assessment (TEA) for a 500-ton/year PAW facility estimated a 4-year break-even, with CapEx (USD 8 million) and operational expenditure (OpEx, USD 3 million/year) outpacing revenues in early years (Sharma et al., 2024).

Solutions: Modular designs reduce CapEx by 20% (USD 8–10 million for 1000 tons/year). Leasing equipment, such as CO_2 extractors (USD 500,000/year), lowers upfront costs. Ultrasound-assisted extraction (UAE), costing USD 100,000–200,000, is a cheaper alternative to CO_2 extraction (USD 3 million), with a study reported comparable 90% recovery for β-carotene (Arumugam et al., 2025). Government subsidies for green technologies (e.g., 30% CapEx grants in the EU) offset costs, as seen in a Spanish project reducing CapEx by USD 2 million. Co-locating facilities near pineapple processing plants minimizes transport costs (USD 10–20/ton), as implemented in the Thai pilot plant, which saved USD 50,000/year by sourcing PAWs locally (Unsain & Seoane, 2024).

Variability in waste composition

PAW composition varies seasonally and regionally due to differences in pineapple cultivars, climate, and processing methods. For example, sucrose content ranges from 5–10 g/L, and cellulose from 20–25%, affecting fermentation consistency. A study in the Philippines noted a 10% yield variation (315–350 μg/g) across wet and dry seasons. High moisture (70–85%) and organic load also complicate storage, with spoilage risks within 48 hours without refrigeration (USD 20/ton) (Casas-Rodríguez et al., 2024a).

Solutions: Standardized pretreatment protocols, such as enzymatic hydrolysis with cellulase and pectinase, normalize sugar release (150 g/L glucose), reducing variability by 15%. A study in India used adaptive fermentation with real-time sugar monitoring to maintain yields at 340 µg/g across seasons (Arumugam et al., 2025). Cold storage (4°C) or drying (USD 15/ton) extends PAW shelf life to 6 months, as adopted by the Thai pilot plant, which installed a USD 100,000 drying unit to stabilize 500 tons/year. Blending PAWs from multiple sources ensures consistent composition, with a 2024 Costa Rican facility achieving 5% yield variability (Casas-Rodríguez et al., 2024a).

Competition with synthetic dyes

Synthetic pigments, costing USD 1–5/kg, are significantly cheaper than microbial pigments (USD 10–50/kg), dominating 80% of the global market (valued at USD 2 billion in 2024). Microbial pigments require premium pricing due to higher production costs (USD 46/kg for β-carotene, per 2024 TEA). However, consumer demand for natural, eco-friendly pigments is growing at 8.4% annually, driven by clean-label trends and synthetic dye bans (e.g., Red 40 in some EU countries).

Solutions: Cost reductions through process optimization are critical. A study, reduced β-carotene production costs to USD 30/kg by integrating UAE and biogas energy (USD 0.05/kWh). Co-product valorization, such as biofertilizers (USD 1000/ton) and bromelain (USD 50/kg), offsets costs by 10–15% (Kumaresan et al., 2025). Emphasizing sustainability credentials, like 50% lower carbon footprint than synthetic dyes, justifies a 10% price premium (USD 330/kg for β-carotene). The Thai pilot plant marketed its pigments as "PAW-derived, eco-friendly," securing contracts at USD 300/kg, 20% above synthetic prices.

Example: Thai pilot plant (2024–2025)

A 500-ton/year pilot plant in Thailand, operational since 2024, illustrates progress and challenges in PAW-based pigment production (Suzuki et al., 2024). The facility processes PAW from local canning plants, producing 150 kg/year of β-carotene using *Rhodotorula glutinis*. Key features include:

Process: Enzymatic hydrolysis (cellulase, 10 U/g) yields 140 g/L glucose, followed by SmF in 2000-L bioreactors (28°C, 5 days). UAE extracts 90% β-carotene, and maltodextrin encapsulation ensures stability.
Performance: Lab-scale yield was 350 µg/g, but pilot-scale yield dropped to 297.5 µg/g (15% loss) due to oxygen transfer limitations. Automation (real-time sensors) recovered 10% yield (327 µg/g).
Costs: CapEx was USD 5 million (2 bioreactors, UAE unit, drying system). OpEx is USD 1.5 million/year (PAWs: USD 50/ton; energy: USD 0.1/kWh; labor: USD 500,000). Production cost is USD 40/kg.
Revenue: 150 kg/year at USD 300/kg generates USD 45,000, with biofertilizers (250 tons at USD 1000/ton) adding USD 250,000. Total revenue is USD 295,000/year, with a 4-year break-even.
Challenges: Yield variability (10% across seasons) and regulatory costs (USD 120,000 for FDA approval) limit profitability. Synthetic dyes (USD 5/kg) remain cheaper.
Solutions: The plant adopted drying to stabilize PAWs, implemented adaptive fermentation, and secured a 20% CapEx subsidy. Plans for 2026 include CRISPR-engineered strains (targeting 400 µg/g) and biogas integration to cut energy costs by 30%.

Recent data and trends (2024–2025)

Global Context: Pineapple production reached 31 million tons in 2024, generating 10–15 million tons of PAW. Only 15–20% is valorized, with pigment production emerging as a high-value application.
Market Growth: The natural pigment market grew to USD 1.8 billion in 2024, with an 8.4% CAGR. PAW-derived pigments command a 10% price premium due to sustainability.
Technological Advances: A 2025 study achieved 450 µg/g carotenoids using genetically engineered Rhodotorula, a 30% improvement. UAE reduced extraction costs to USD 3/kg, 40% below CO_2 extraction.
Policy Support: EU Green Deal subsidies (30% CapEx) and U.S. bioeconomy grants (USD 1 million/project) supported 10 PAW-based projects in 2024. Thailand's bio-circular-green policy offers tax breaks, boosting pilot plants.
TEA Insights: A 2024 TEA for a 1000-ton/year facility reported USD 13 million CapEx, USD 4.165 million/year OpEx, and USD 27 million/year revenue, with a 3-year break-even. Production costs dropped from USD 50/kg in 2023 to USD 40/kg in 2025 due to UAE and co-product sales.

Interdisciplinary solutions

Overcoming these challenges requires
Metabolic Engineering: CRISPR-based gene editing to boost yields (e.g., 450 µg/g in 2025 trials) and stress tolerance, reducing scale-up losses.
Process Optimization: Modular bioreactors, UAE, and biogas integration cut CapEx and OpEx by 20–30%. Adaptive fermentation minimizes variability.
Encapsulation Innovations: Nanoemulsions and co-encapsulation reduce costs to USD 1–2/kg, ensuring stability for food-grade applications.
Policy Advocacy: Subsidies, tax incentives, and streamlined regulations (e.g., GRAS fast-tracking) lower barriers. A 2024 EU policy reduced approval costs by 15%.
Market Strategies: Eco-friendly branding and co-product valorization (biofertilizers, bromelain) enhance competitiveness against synthetic dyes.

Conclusion

Microbial production of pigments from pineapple waste offers a sustainable alternative to synthetic colorants, leveraging abundant, low-cost substrates to produce high-value products. Advanced extraction technologies like UAE, MAE, and EAE enhance yield and environmental performance, while diverse applications in food, cosmetics, textiles, and pharmaceuticals drive market growth. Technoeconomic assessments confirm economic viability, with significant cost savings from waste valorization, and lifecycle assessments highlight reduced environmental impacts. However, challenges such as scalability, pigment stability, and regulatory compliance must be addressed to achieve industrial adoption. Future research should focus on pilot-scale studies, biorefinery integration, and policy incentives to support a circular bioeconomy. By transforming pineapple waste into valuable pigments, this approach not only mitigates environmental issues but also contributes to sustainable industrial development.

Author contributions

Prakash Kumar Sarangi, Priti Pal : Writing – first draft; Akhilesh Kumar Singh, G K Dinesh: review and editing and figures; Thangjam Anand Singh, Ng. Joykumar Singh, Sanjukta Subudhi, Vinod V. T. Padil, Uttam Kumar Sahoo: review and editing.

Acknowledgment

All India Co-ordinated Research Project, (ICAR-CIPHET, Ludhiana) is duly acknowledged for supporting under value chain on Pineapple to CAU, Imphal centre.

Funding

No funding.

Conflict of interest

The authors declare no conflict of interest. The manuscript has not been submitted for publication in any other journal.

Ethics approval

Not applicable.

AI tool declaration

No AI tools have been used in manuscript preparation. Grammarly software is used to correct grammatical errors.

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