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BIOREFINERY STRATEGIES FOR WASTE VALORIZATION OF TROPICAL FRUITS: A REVIEW

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ABSTRACT

Tropical fruits constitute a vital component of global flora, fostering biodiversity, and providing essential nutrients to enrich diets. Recent years have witnessed a consistent rise in their production. This surge in production and processing has led to a corresponding increase in waste, posing significant environmental challenges. This jeopardizes sustainability goals and underscores the urgency for eco-friendly development practices. It is noteworthy that these fruit wastes harbour potent bioactive properties, presenting a valuable resource for innovative waste management strategies. Through various processing techniques, such as biochar production, extraction of bioactive compounds, and creation of biopolymers, these wastes can be transformed into a myriad of useful products. Integration of these processes into biorefinery frameworks offers a holistic and sustainable approach to waste management in the processing industry. The establishment of integrated biorefineries requires careful consideration of both technological advancements and economic viability, alongside comprehensive life cycle assessments. Such endeavours aim to ensure the development of environmentally friendly models that align with principles of sustainability. In this review, we delve into the intricacies of waste valorisation from tropical fruits, exploring diverse processes and conditions to ensure maximum positive outcomes.

Keywords **:** Tropical fruit waste, Biorefinery, Waste valorisation, Bioactive compounds, Bioenergy, Biopolymers

Introduction

Fruits are an indispensable component of the human diet, serving as primary biological reservoirs for dietary fibre, organic acids, vitamins, and minerals essential for global nutritional security. Tropical species, most notably banana, mango, avocado, pineapple, and papaya occupy a critical niche in world agricultural production. Driven by surging consumer demand and optimized supply chain logistics, the global fruit sector has demonstrated consistent economic expansion; FAOSTAT data reveals a value increase of approximately 5.83% from 2020 to 2023 (FAO, 2025). This growth highlights a burgeoning bio-resource base that remains largely underutilized within traditional waste management streams, despite being driven by a rising population and increased health consciousness among consumers seeking natural antioxidants.

To address this underutilization, biorefinery approaches are increasingly undertaken to mitigate environmental harm while simultaneously creating new value chains within a circular economy. A biorefinery is not merely an isolated entity but a sophisticated technological framework capable of fractionating biomass into its constituent carbohydrates, proteins, and fats (Cherubini and Strømman, 2011). This strategy encompasses a series of sequential procedures, commencing with feedstock selection and pre-treatment, followed by multi-step biological or chemical treatments (Strezov and Tim, 2014). Beyond simple conversion, the significance of these systems lies in their inherent capability to address the "sustainability triad" balancing economic, social, and environmental considerations (Sonnenberg *et al.*, 2009). By viewing waste as a valuable resource rather than a burden, the biorefinery concept becomes a central pillar in propelling a sustainable global bio economy. This review was conducted through a comprehensive literature survey aimed at identifying relevant studies on the valorisation of tropical fruit waste within biorefinery frameworks. Scientific databases including Scopus, Web of Science, and Google Scholar were systematically searched to obtain peer-reviewed publications.

Tropical fruit by-products: Morphology and composition

Tropical regions abound with an array of flavourful fruits that, during industrial processing transforms into juices, jams, and pickles, yield substantial volumes of diverse waste materials. These residues, including peels, seeds, pomace, and pulp, are frequently relegated to discarded waste despite being enriched with bioactive compounds and essential biomolecules. Indeed, studies have confirmed that the antioxidant characteristics of these by-products are often comparable to those found in raw fruits, underscoring their significant post-processing nutritional value (Aguedo *et al.*, 2012). The quantity and nature of generated waste are strictly dictated by fruit morphology. For instance, the pineapple processing industry generates approximately 50% waste, which includes the crown, peel, core, and pomace (Rabiu *et al.*, 2018), whereas avocado processing regards roughly 30% of the fruit specifically the peels and kernels as bio-waste (Melgar *et al.*, 2018). Similarly, papaya processing yields by-products such as peels and seeds constituting 12% and 8.5% of the total weight, respectively (Pathak *et al.*, 2019). In the case of mango, while the edible portion constitutes 50% to 60% of the weight, the remaining 25% to 40% inevitably ends up as a byproduct (Lebaka *et al.*, 2021). Banana residues are equally significant, with peels alone representing roughly 40% of the fresh fruit weight (Kamble *et al.*, 2017). Furthermore, citrus residues offer a complex matrix of flavedo and albedo, which are not only abundant in pectin and sugars but also feature high concentrations of D-limonene, a potent antimicrobial compound (Choi *et al.*, 2015).

Chemical investigations further highlight the versatility of these residues. Gupta *et al.* (2012) confirmed the existence of both saturated and unsaturated free fatty acids, alongside essential minerals such as calcium, potassium, magnesium, sodium, and phosphorus within fruit residues. Specifically, acerola fruit residue has been identified as a rich source of anthocyanins and vitamin C, while cashew apple and pineapple residues provide vital unsaturated fatty acids and manganese (Sancho *et al.*, 2015). Such diverse composition provides the foundation for the following sections of this review, which explore multifaceted applications ranging from bioactive extraction to the synthesis of nanocellulose, biopolymers, and sustainable energy carriers like biofuels and biochar.

Bioactive valorisation: from phytochemical profiling to therapeutic potential

The transition of tropical fruit residues from "waste" to "resource" is underpinned by their dense concentration of secondary metabolites, which often exceed levels found in the edible flesh (Aranguren *et al.*, 2018). For instance, the seeds of jackfruit, longan, and avocado exhibit significantly higher phenolic content and antioxidant capacity than their respective pulps (Soong and Barlow, 2004). The discarded components of tropical fruits reveal a multifaceted bioactivity spectrum. Beyond simple nutritional value, these fractions exhibit specialized medicinal properties:

a) **Anti-proliferative and Cytotoxic Effects:** Mango seed kernels, characterized by abundant oleic and stearic acids alongside gallotannins, have demonstrated selective anti-proliferative activity against the human colon adenocarcinoma cell line HT-29 (Ballesteros-Vivas *et al.*, 2019). Similarly, banana peel flavonoids attenuate the production of nitric oxide and nuclear factor-kB (NF-kB), inhibitory mechanisms pivotal in halting cancer progression (Oliveira *et al.*, 2020).

b) **Anti-inflammatory and Analgesic Potential:** High-value compounds in pomegranate rinds play a critical role in mitigating inflammatory conditions like rheumatoid arthritis. Research indicates that pomegranate extracts (200 mg/kg) can significantly reduce pain and inflammation by down-regulating tumor necrosis factor-alpha, tumour necrosis factor R1, interleukin-1β, interleukin-6, nuclear factor-κB, and oxidative stress markers (Karwasra *et al.*, 2019).

Table 1 : Fruit by-products and their bioactive properties

Biomass	**Bioactive properties**	**Reference**
Rambutan peels	Antioxidant properties and antimicrobial properties	(Albuquerque *et al*., 2023)
Soursop pulp and seeds	Antidiarrheal activity, Thrombolytic, antimicrobial, anti-tumor, anti-oxidant properties	(Afroz *et al*., 2020), (Raybaudi-Massilia *et al*., 2015)
Pomegranate peels	Lipid regulation, Immunomodulation, anti-inflammatory, antiviral, antibacterial properties	(Grabež *et al*., 2020; Haghighian *et al*., 2021)
Passionfruit seeds	Anti-proliferative and anti-cancer properties	(Ballesteros-Vivas *et al*., 2020; Kasala *et al*., 2016)
Jackfruit rags and peels	Anti-oxidant and anti- bacterial properties	(Tran *et al*., 2023)
Pineapple crown	Anti-oxidant and anti- microbial properties	(Brito *et al*., 2021)
Dragon fruit peels	Anti-inflammatory and anti-angiogenic properties	(Rodriguez *et al*., 2016)
Citrus peels	Anti- aging properties, anti- melanogenic, anti-oxidant properties	(Prommaban & Chaiyana, 2022)
Mangosteen pericarp	promotes hair growth and tanning activities on hair dermal papilla cells Antioxidant properties	(Tan *et al*., 2022; Thong *et al*., 2015)
Avocado seeds	Neuroprotective activity, antioxidant properties, anti-microbial properties and anti-cholinergic properties	(Grisales-Mejía *et al*., 2024; Soledad *et al*., 2021)

c) **Antimicrobial and Anti-fungal Applications:** The peels of *Hylocereus spp.* (Pitaya) exhibit significant antibacterial activity against a range of pathogens, particularly when extracted with chloroform (Nurmahani *et al*., 2012). Furthermore, orange peel extracts rich in ferulic and p-coumaric acids serve as natural fungicides against *Botrytis cinerea* and *Alternaria alternata*, suggesting their potential as bio-alternatives to chemical preservatives for extending fruit shelf-life (Hernández *et al*., 2021).

Furthermore, the efficiency of a biorefinery depends on understanding the chemical "fingerprint" of the feedstock. Table 1 and Table 2 provide exhaustive data on various techniques used for extraction and bioactive properties of these waste residues, certain tropical residues stand out for their exceptional density: In avocados, the "Hass" variety displays a unique size-dependent profile where smaller, typically discarded fruits contain higher total phenols and flavonoids in their peels than larger counterparts (Trujillo-Mayol *et al*., 2020). Other specific markers include the unique polyphenolic xanthones ±-mangostin and ^{3}-mangostin in mangosteen pericarp (Cho *et al*., 2020).

Advanced and Sustainable Extraction Strategies

To align with green chemistry, the recovery of these compounds is shifting toward sustainable solvent systems and hydrothermal processes. Natural Deep Eutectic Solvents (NADES) have emerged as eco-friendly alternatives for recovering sterols, tocopherols, and terpenes (Benvenutti *et al*., 2020). Innovation in extraction technology significantly impacts yield. For Gac fruit (*Momordica cochinchinensis*), Ultrasound-Assisted Extraction (UAE) consistently outperforms Microwave-Assisted Extraction (MAE) in maximizing lycopene and beta-carotene recovery (Chuyen *et al*., 2018). Furthermore, semi-continuous high-pressure hydrothermal processing has proven effective for pitaya peels, where phenolic concentrations peak at temperatures of 210°C (41.61 mg/g). These extracted constituents encompassing sterols, carotenes, and polyphenols hold immense potential for the formulation of high-performance functional foods with enhanced antioxidant characteristics (Ferreira *et al*., 2023).

Biofuels and Bioenergy: Sustainable Energy Carriers

In the context of the International Energy Agency’s (IEA) "Net Zero Emissions by 2050" scenario, sustainable biofuels and clean fuels like hydrogen are projected to play a pivotal role in decarbonizing the transportation sector. The demand for these biofuels is anticipated to triple between 2021 and 2030, highlighting the urgent need for scalable, non-food feedstocks (IEA, 2023). Tropical fruit wastes, characterized by high levels of fermentable sugars and lignocellulosic carbohydrates, are increasingly recognized as viable substrates for this energy transition (Jahid *et al*., 2018).

The production of liquid biofuels from fruit residues primarily hinges on the efficiency of sugar release and subsequent fermentation. While yields vary by species (Table 3), the morphological characteristics of the waste significantly influence the process; in jackfruit (*Artocarpus heterophyllus*), the starch-rich seeds (stones) of jackfruit represent a high-density energy source. Research has shown that acid-catalyzed hydrolysis using HCl yields a higher bioethanol content (19.24%) compared to enzymatic methods (17.36%). Notably, the physical resilience of dried jackfruit stones allows for extended storage up to one year without microbial degradation offering a strategic advantage for year-round biorefinery operations (Nuriana & Wuryantoro, 2015). Moreover, utilizing pineapple waste as a carbon source for *C. beijerinckii* TISTR 1390 yields butanol at concentrations of 3.14 ± 0.16 g/L. Although this yield (0.08 g/g) is lower than other industrial feedstocks, the process is economically attractive because pineapple waste juice requires no pre-treatment or hydrolysis, significantly reducing operational costs (Sanguanchaipaiwong & Leksawasdi, 2018).

Beyond fermentation, the lipid-rich seeds of tropical fruits offer a pathway to biodiesel through transesterification. A critical illustration is the use of Sapota Methyl Ester (SME) derived from sapota fruit seeds. Investigations into engine performance using a B50% blend (50% SME and 50% diesel) in a Common Rail Direct Injection (CRDI) engine revealed that optimizing the compression ratio (CR) and exhaust gas recirculation (EGR) can significantly mitigate emissions. The optimal configuration (CR 16 and EGR 20% at full load) demonstrates that tropical fruit-based biodiesels are not only viable fuel substitutes but can be integrated into modern engine systems to promote a circular bioeconomy and reduce greenhouse gas outputs (Jayabal *et al*., 2020).

Table 2: Tropical fruit by-products and bioactive compounds

Biomass	**Bioactive compounds**	**Extraction technology**	**References**
Mango peels	Quercetin, Mangiferin, gallate derivatives	MAE with pre-extraction process using SFE	(Sánchez-Camargo *et al*., 2021)
Passion fruit rinds and bagasses	Isoorientin, vicenin, vitexin, orientin, isovitexin	Ultrasound- Assisted Pressurized Liquid Extraction (UAPLE)	(Pereira *et al*., 2021)
Pineapple peels	Phenolic compounds Bromelain	Microwave- assisted extraction	(Bansod *et al*., 2023)
Papaya seeds	Mandelic acid, vanillic acid, ferulic acid	Subcritical water extraction	(Gonçalves Rodrigues *et al*., 2019)
Mango seeds	Ethyl gallate, penta-O-galloyl-glucoside and rhamnetin derivatives	Microwave-assisted extraction	(Torres-León *et al*., 2017)
Avocado peels	Phenolic acids, flavonoids, catechins, and procyanidins	Microwave-assisted extraction	(Araujo *et al*., 2021)
Pomegranate peels	Anthocyanins and phenolic compounds	Ultrasound assisted extraction	(Sharayei *et al*., 2019)
Mangosteen pericarp	α-mangostin, phenolic compounds	Microwave assisted extraction	(Mohammad *et al*., 2019)
Citrus peels	Neoesperidin, Rutin, narirutin, bergamottin, imperatorin, citropten, phenol compounds Hesperidin	HPLC–photodiode array–mass spectrometry (MS) CO_2-responsive deep eutectic solvents extraction	(Russo *et al*., 2014) (S. Wang *et al*., 2024)
Banana peels	Phenolic compounds, flavonoids	Ultrasound- assisted extraction	(Granella *et al*., 2023)
Jackfruit peels	Pectin	Radio frequency assisted extraction	(Naik *et al*., 2020)

Bio-hydrogen and Gaseous Bioenergy

Advanced fermentation techniques are also being applied to high-sugar tropical residues to produce gaseous energy carriers. In a study of 'Deglet Nour' date flesh, dark fermentation conducted without inoculation demonstrated significant bio-hydrogen potential. Furthermore, the extraction of date syrup (yield of 0.73 g/g) followed by anaerobic digestion of the remaining crude fibers showcases a "zero-waste" cascading approach to bioconversion (Yahmed *et al*., 2021). In biorefineries, the final energy recovery from biodegradable materials can be achieved through anaerobic digestion, where organic matter is biologically broken down in the absence of oxygen to produce methane-rich biogas (Bhatia, 2014). This represents the most straightforward bioenergy alternative in terms of production and purification (Gnansounou & Raman, 2019). Fruit processing waste is particularly suited for this pathway as it contains an abundance of simple sugars and disaccharides that readily undergo methanogenesis to produce volatile fatty acids (VFA) as intermediaries (Schnürer & Jarvis, 2009).

Table 3: Tropical fruit waste and various fuels obtained

Feedstock	Methods used	Products obtained	Yield	Reference
Mangosteen pericarp	*Separate hydrolysis and fermentation (SHF)*	Bioethanol	75 %	Cho *et al*., 2020
Passion fruit seeds	*Soxhlet extraction with n-hexane*	Bio-oil	26.12%	Pereira *et al*., 2019
Avocado seeds	*Milling and Enzymatic hydrolysis*	Bio-ethanol	178 mL kg^{-1}	Vintila *et al*., 2019
*Banana pseudo stem	*Separate hydrolysis and fermentation process*	Acetone-butanol-ethanol	0.39 gg^{-1}	Alzate Acevedo *et al*.,2021
Mango peels	*Pyrolysis*	Bio- hydrocarbons	23.3 %	Tahir *et al*., 2021
Dragon fruit peels	*Fermentation*	Bio- ethanol	64.5%	Sarungu *et al*., 2022
Pomegranate seeds	*Microwave assisted extraction*	Bio-oil	17.64%	Rojo-Gutiérrez *et al*., 2021
Avocado peels	*Transesterification*	Bio-diesel	95.2%	Bullo *et al*., 2021

The efficiency of biogas generation is highly sensitive to influential factors such as pH, substrate nature, and retention time. Optimal biogas generation from mango, papaya, and watermelon waste typically manifests at temperatures between 28 and 35°C (Chinwendu *et al*., 2019). Papaya (*Carica papaya*) peels, specifically, are noted for their high mineral composition and methane content. The application of thermo-alkaline pretreatment has been demonstrated to improve substrate breakdown in these peels, increasing biogas yields by 26.52% compared to untreated samples (Dahunsi *et al*., 2017). Ultimately, leveraging tropical fruit waste for biogas not only addresses environmental disposal concerns but also optimizes the conversion of underutilized organic nutrients into a sustainable source of bioenergy.

Solid residue valorisation: biochar and functional biosorbents

A different direction of the tropical fruit biorefinery involves the transformation of recalcitrant solid residues into stable carbon materials, effectively closing the loop on the circular economy. This is primarily achieved through pyrolysis, a thermochemical decomposition process conducted at elevated temperatures in the absence of oxygen, which yields a structurally stable, carbon-dense substance known as biochar (Glaser *et al*., 2009). Beyond its role in sustainable waste management, biochar acts as a critical agent for carbon sequestration and soil improvement, with documented efficacy in enhancing soil fertility and microbial health (Deshoux *et al*., 2023). However, the optimization of biochar application requires a strategic approach tailored to specific soil morphologies and nutrient requirements (Freitas *et al*., 2019).

Table 4 : Fruit waste, biochar yield and procedure followed

Substrate	Procedure followed	yield	Reference
Pineapple peels	Torrefaction at 210-300°C, 30-60 min	HHV- 20-28 MJ/kg Energy yield- 76-88% [HHV- Higher heating value]	(Lin *et al*., 2021)
Custard apple peels	Torrefaction at 210-300°C, 30-60 min	HHV- 19-23 MJ/kg Energy yield- -65-83%	(Lin *et al*., 2021)
Mango endocarp	Pyrolysis at 300° C, 8 hours	2.8 Kg	(Olawale Olufunmi & Akin Akintola, 2019)
Pineapple pulp	Pyrolysis at 300° C, 8 hours	2.8 Kg	(Olawale Olufunmi & Akin Akintola, 2019)
Avocado seeds	Torrefaction at 304°C	LHV- 23.2 MJ/kg Energy yield- 76.7 %	(Sánchez *et al*., 2017)
Orange peels	Pyrolysis at 350° C, 3 hours	32.5 ± 1.5 %	(Sial *et al*., 2019)
Sour sop	Slow pyrolysis at 400° C	32.2 %	(Schroeder *et al*., 2017)
Mango peels	Pyrolysis at 600º C	966 ± 5 g/kg	(Majumder *et al*., 2022)

Tropical fruit residues are particularly advantageous for biochar production as given in table 4 due to their high mineral content, specifically potassium (K). Research on durian shell biochar revealed exceptional K concentrations (51,000 mg/kg), with approximately 50% of this content being water-soluble and readily available for plant uptake (Prakongkep *et al*., 2015). Such characteristics suggest that these bio-based carbons could serve as sustainable substitutes for conventional water-soluble fertilizers like potassium chloride. Similarly, banana peel biomass has emerged as a high-performance precursor for biochar. Optimal yield (58.8%) and agronomic performance are achieved through slow pyrolysis at 356.1°C with a 180-minute residence time. When applied to soil at a 1% dosage, this biochar significantly improved the growth of *Ipomoea aquatica*, highlighting the practical viability of low-temperature pyrolysis for enhancing agricultural output (Te *et al*., 2021).

Parallel to soil applications, these biological materials can be engineered into biosorbents for the remediation of aqueous pollutants. Biosorption leverages the inherent functional groups such as carboxylic and hydroxyl groups, found in plant tissues to bind and accumulate ions, metals, and organic molecules (Volesky, 2007). Banana peels have been successfully fabricated into carbon foams capable of the concurrent removal of Cu (II), Pb(II), Cd(II), and Cr(VI), achieving over 98% sequestration of targeted heavy metals within 60 minutes through hydrothermal calcination (Li *et al*., 2016). The presence of acidic surface groups on modified banana peels is also instrumental in the removal of cationic dyes like Rhodamine B, facilitating the adsorption of positively charged molecules (Oyekanmi *et al*., 2019)

The selectivity of these biosorbents can be further refined through chemical activation. For instance, mangosteen pericarp gels activated via saponification demonstrate a distinct affinity for heavy metals in a selectivity order of Fe (III) > Pb(II) > Cu(II). Furthermore, composite materials like rarasaponin–bentonite-activated biochar from durian shells have proven effective for the simultaneous removal of Crystal violet and Cr (VI). These dual-pollutant systems reveal that adsorption efficiency is highly temperature-dependent; while Crystal violet removal is optimal at higher temperatures, Cr (VI) adsorption is superior at lower temperatures (Laysandra *et al*., 2018). This underscores the necessity of tailoring operating conditions to the specific chemical characteristics of the targeted pollutants to ensure maximum efficiency in industrial wastewater treatment.

Advanced Material Recovery

Another tier of the tropical fruit biorefinery focuses on the conversion of lignocellulosic and fermentable fractions into advanced biomaterials. By integrating material science with microbial biotechnology, these processes ensure that even the most recalcitrant fruit components such as shells and spent peels are transitioned into high-value product chains.

Nanocellulose Extraction and Bacterial Cellulose Synthesis

Nanocellulose has emerged as a premier biomaterial due to its amorphous and crystalline domains, which impart high mechanical strength, an elevated Young's modulus, and low gas permeability (Kotov *et al*., 2023; Pértile *et al*., 2012). The physicochemical attributes of these nanostructures are significantly dictated by the cellulose source and extraction parameters (Barampouti *et al*., 2021). For instance, citrus biomass waste is a prolific source of nanocellulose through a sequence of alkaline treatment and acid hydrolysis, which reduces fiber size to create an amorphous structure (Naz *et al*., 2016). Similarly, previously disregarded residues such as bael fruit shells have been identified as a prospective reservoir for cellulose nanocrystals (CNCs). Synthesis via mechanical and chemical procedures yields CNCs with heightened crystallinity and thermal stability, offering significant potential for reinforcing bio-composite applications (Sathwane *et al*., 2024).

Beyond plant-derived cellulose, tropical fruit residues including pineapple, orange, sweet lime, and banana serve as sustainable substrates for bacterial cellulose (BNC) production. BNC synthesized from these wastes often exhibits mechanical properties and water retention capabilities that surpass those derived from conventional mediums (Khan *et al*., 2021). Innovative frameworks such as ultrasonic-assisted dilute acid hydrolysis (UADAH) allow for the concurrent generation of essential oils, pectin, and BNC from orange peel waste, yielding approximately 5.82 g of cellulose per 100 g of waste (Karanicola *et al*., 2021). Furthermore, the conversion of banana peel powder into nanocrystalline cellulose (NCC) through alkali-bleaching and acid hydrolysis establishes a crystalline structure suitable for multifaceted applications, ranging from tablet excipients in oral drug delivery to conductive films in biosensors (Mishra *et al*., 2022). To optimize yields, modern methodologies like atmospheric cold plasma (ACP) are employed to detoxify hydrolysates by eliminating inhibitory compounds like formic acid and furfural (Santoso *et al*., 2021).

Biopolymer Development

Biopolymers represent a renewable and low-cost alternative to petrochemical plastics, particularly in high-precision sectors such as pharmaceuticals, tissue engineering, and food packaging (Smith *et al*., 2016; Ma *et al*., 2024). Amidst them, polyhydroxybutyrate (PHB) is a key biopolymer that shares mechanical similarities with polypropylene but often suffers from higher production costs. However, by utilizing residual banana waste within an integrated biorefinery framework, mass and energy integration strategies can achieve substantial savings, enhancing the economic viability of PHB (Naranjo *et al.*, 2014). Additionally, starch-rich residues like jackfruit seed powder have proven to be cost-effective substrates for Xanthan gum (XG) production. Through aerobic submerged fermentation by Xanthomonas campestris, yields of up to 51.62 g/L can be achieved when medium components like K_2HPO_4 and KH_2PO_4 are optimized to serve as both buffers and nutrients (Felicia Katherine *et al.*, 2017).

Table 5 : Fruit by-products and biopolymer produced

Type of polymer produced	Biomass	Method used	Reference
Poly lactic acid	Banana and pineapple residues	Microwave assisted synthesis direct melt polycondensation	(Jiménez-Bonilla *et al.*, 2014)
Polyhydroxyalkanoates	Pineapple peel Orange & passionfruit wastes	Submerged fermentation Batch fermentation	(Vega-Castro *et al.*, 2016) (Locatelli *et al.*, 2019)
Polyhydroxy butyrate	Pineapple peels Banana peels	Batch fermentation Submerged fermentation Submerged fermentation	(Vega-Castro *et al.*, 2016) (S. Maity *et al.*, 2020)

Future Prospects and Challenges

The transition from laboratory-scale waste valorisation to industrial-integrated biorefineries represents the next frontier in tropical fruit processing. While breakthroughs in extraction and bioprocessing (e.g., the hydrothermal-alkali methods for pineapple waste) have demonstrated the ability to yield high-value fractions like bromelain, xylo-oligosaccharides (XOS), and fermentable glucose (Banerjee *et al.*, 2018), several systemic hurdles remain.

A primary challenge lies in the inherent nature of tropical fruit waste, i.e., high moisture content and rapid microbial degradation. Future strategies must move beyond immediate processing to the development of stable intermediates. By segregating biomass into its primary constituents namely, cellulose, hemicellulose, and lignin at the source, facilities can extend storage life and ensure a steady feedstock supply (Maity, 2015). Furthermore, the design of "bio-clusters" offers a promising path forward, where downstream residues from one process become the upstream raw materials for another, effectively closing the loop on material flow (Cherubini, 2010).

For a biorefinery to be commercially viable, its products must be economically competitive with fossil-fuel-based alternatives. Future research must prioritize integrated multi-feedstock schemes that allow facilities to remain operational year-round despite the seasonality of specific tropical fruits (Manhongo *et al.*, 2022). The use of Life Cycle Assessment (LCA) is non-negotiable in this transition. Current data suggests that raw material production and pre-treatment are the heaviest contributors to environmental burdens (Santiago *et al.*, 2022). Therefore, future efforts should focus on Internal Energy Circularity by meeting heat and electricity demands through the onsite combustion of final residues along with utilizing cross-disciplinary collaboration to lower the capital expenditure of advanced extraction technologies (Sarangi *et al.*, 2023).

Conclusion

The valorisation of tropical fruit waste through integrated biorefinery strategies offers a dual solution to environmental degradation and resource scarcity. By shifting the perspective of "waste" to "valuable feedstock," the industry can produce a spectrum of high-value compounds from therapeutic enzymes to biofuels within a circular economy framework. However, the path to industrialization requires overcoming significant bottlenecks in biomass stabilization, technological scalability, and market-aligned production. The future of tropical fruit processing lies not in isolated extraction methods, but in synchronized, multi-product systems that are techno-economically resilient. As processing industries move toward treating waste valorisation as a core concurrent operation rather than an afterthought, they will play a pivotal role in the global shift toward a sustainable, bio-based economy.

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