Microalgal Bioprocessing of Fruit Peel Waste for Sustainable Bioplastics

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Abstract
The increasing volume of agro-industrial waste and the detrimental impact of conventional plastics on the environment necessitate the development of sustainable, integrated bioprocessing solutions. This study focuses on using fruit peel waste as an affordable substrate for the growth of microalgae, specifically *Chlorella* and *Spirulina*, to produce biodegradable bioplastics and agricultural bioinputs. Fruit peel hydrolysates rich in fermentable sugars and nutrients will be employed to enhance microalgal growth under optimal conditions, while nutrient stress will be applied to encourage the accumulation of polyhydroxyalkanoates (PHAs). The collected biomass will be processed for polymer extraction and characterization using state-of-the-art analytical techniques. After extraction, plant growth tests will be used to evaluate the remaining biomass, which will next be studied as a nutrient-rich biofertilizer.
By addressing waste management, sustainable bioplastic manufacturing, and improving soil health all at once, this integrated method seeks to create an economical and environmentally friendly biorefinery model. The results of this study are expected to support sustainable farming methods, reduce reliance on fossil-fuel-derived plastics, and aid in the development of circular bioeconomy frameworks.
Keywords: Biofertilizer, Bioplastics, Biorefinery, Fruit Peel Waste, Microalgae.

1. Introduction

The rapid increase in agro-industrial waste and plastic pollution has created serious environmental challenges worldwide. Fruit peel waste, a major byproduct of food processing industries, is rich in carbohydrates, minerals, and bioactive compounds, making it a promising low-cost substrate for biotechnological applications. At the same time, conventional plastics derived from fossil fuels contribute significantly to environmental degradation [1].

Large quantities of fruit peel waste remain underutilized, leading to disposal and pollution issues. Rising demand for eco-friendly alternatives to petroleum-based plastics necessitates sustainable bioplastic production. Current bioplastic production processes are expensive due to costly substrates. There is a need for integrated systems that generate multiple value-added products (bioplastics + biofertilizers). Microalgae-based bioprocessing offers a green and scalable solution but requires optimization for waste utilization and product yield [6, 7]. India generates ~50 million tons of fruit peel waste annually, primarily citrus and banana, creating environmental disposal challenges while offering untapped nutrient potential. This postdoctoral proposal develops a zero-waste cascade biorefinery converting peel hydrolysates into (1) PHA bioplastics from Chlorella vulgaris and (2) protein/NPK-rich biofertilizers from Spirulina platensis post-extraction residues. Food waste is a major global problem that affects the sustainability of food systems. It leads to inefficient use of resources, environmental damage, economic losses, and social inequalities. The impacts of food waste include financial losses, rising food prices, higher waste disposal costs, food insecurity, health concerns, greenhouse gas emissions, depletion of natural resources, pollution, and loss of biodiversity [11].

Food processing industries, especially fruit processing units, generate huge amounts of waste such as peels, seeds, and pulp residues. Although often discarded, these by-products are rich in valuable bioactive compounds like antioxidants, flavonoids, dietary fiber, phenolics, and minerals that can be used in nutraceutical and health-related products. Modern biorefinery approaches aim to convert this low-cost agro-industrial waste into useful products, including biofuels and other value-added materials, helping reduce environmental pollution while supporting sustainable resource utilization [8]. The growing focus on a circular economy encourages better use of fruit waste by turning it into valuable products instead of simply discarding it. Fruit processing industries produce large amounts of waste. If left unmanaged, fruit and vegetable wastes decompose and release greenhouse gases like methane, contributing to climate change. They can also pollute water sources through nutrient-rich runoff, leading to eutrophication and harming aquatic ecosystems [9, 10].

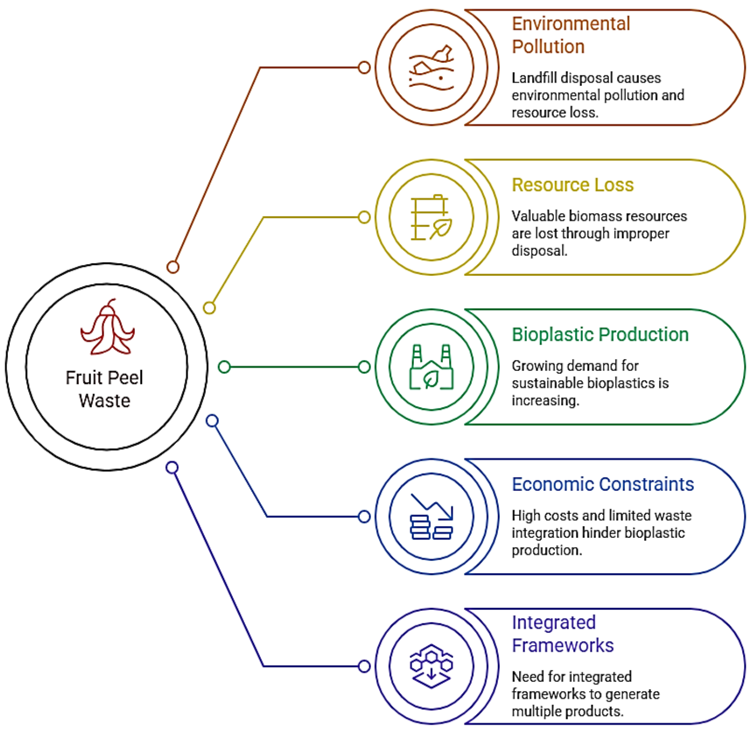

Figure 1. Challenges and Opportunities Associated with Fruit Peel Waste Utilization.

Figure 1 illustrates the major environmental and economic concerns related to fruit peel waste along with its potential applications in sustainable bioplastic production. Improper disposal of fruit peel waste contributes to environmental pollution and resource loss, while the increasing demand for eco-friendly bioplastics highlights its value as a renewable biomass resource. The figure also emphasizes economic limitations and the need for integrated biorefinery frameworks to efficiently convert fruit waste into multiple value-added products [11].

2. Fruit Peel Waste: Composition and Characteristics

Several studies have reported that fruit peels are rich sources of bioactive compounds with significant nutraceutical and pharmaceutical potential. Apple peels contain important phenolic compounds such as quercetin, chlorogenic acid, tannins, and phloridzin, which exhibit strong antioxidant and anti-inflammatory properties [12, 13]. Mango peels are abundant in mangiferin, quercetin, catechins, and carotenoids, including beta-carotene, contributing to their antioxidant and antimicrobial activities [14, 15]. Similarly, banana peels possess flavonoids, dopamine, quercetin, carotenoids, and tannins that have potential applications in food, pharmaceutical, and biomedical industries [16, 17]. Papaya peels are also recognized for their high content of carotenoids such as lycopene and beta-carotene, along with flavonoids like apigenin, which are associated with antioxidant and health-promoting effects. These findings highlight the importance of fruit peel waste as a sustainable source of valuable bioactive compounds for industrial and environmental applications [18].

Fruit peel waste is valuable and sustainable biomass resource rich in bioactive compounds, dietary fiber, minerals, antioxidants, and other important nutrients. Peels from fruits such as citrus, banana, mango, grape, apple, and pear have significant potential for use in food, pharmaceutical, agricultural, nutraceutical, and bioplastic industries. Instead of being discarded as waste, these by-products can be converted into useful value-added products such as biofertilizers, biofuels, functional foods, and biodegradable bioplastics through sustainable bioprocessing approaches. Proper utilization of fruit peel waste not only helps reduce environmental pollution and waste accumulation but also supports circular bioeconomy practices, resource recovery, and eco-friendly industrial development.

3. Bioprocessing of Fruit Peel Waste Using Microalgae

The study demonstrated the effective use of pumpkin, papaya, and orange peels as low-cost substrates for *Chlorella sorokiniana* cultivation in a sustainable biorefinery approach. Under optimized conditions, the microalga produced 3.16 g L^{-1} biomass, 1.55 g L^{-1} lipids, and 9.18 mg L^{-1} carotenoids, with high palmitic acid content (47.9%). Residual biomass was successfully converted into biochar at 350 °C and applied as a soil amendment for Vigna radiata, highlighting its potential for integrated waste valorization and sustainable agriculture [3, 4].

Hwang et al. (2021) demonstrated the potential of fruit peel extracts as sustainable and low-cost culture media for the growth of Anabaena cylindrica. The study reported the highest biomass production in 20% papaya peel medium, while the maximum growth rate was observed in 10% pineapple peel medium, outperforming the conventional BG-11 medium. These findings highlighted the feasibility of utilizing fruit waste as an economical alternative medium for cyanobacterial biomass and biofuel production [19].

Recent research showed that pumpkin, papaya, and orange peel wastes can be effectively used as substrates for Chlorella sorokiniana cultivation. Under optimized conditions, maximum biomass (3.16 g L^{-1}), lipid productivity (1.55 g L^{-1}), and carotenoid productivity (9.18 mg L^{-1}) were achieved. The residual biomass was further converted into biochar at 350 °C and successfully applied as a soil amendment for Vigna radiata. This study supports a sustainable closed-loop biorefinery approach for waste valorization and agricultural applications [3].

Another study investigated the utilization of orange peel waste extract (OWE) as an alternative carbon source for cultivating Nannochloropsis oculata. The highest biomass yield (450 mg L^{-1}) and oil content (28%) were obtained under photoheterotrophic conditions. The produced lipids showed a high proportion of monounsaturated fatty acids (77.49%), which are favorable for biodiesel production. Furthermore, a microwave-assisted one-pot extraction method efficiently converted the algal oil into glycerol-free biodiesel, highlighting the potential of orange peel waste for sustainable biofuel generation and agro-waste valorization [2, 5].

Research Gap

- Most studies on microalgae cultivation use costly synthetic media instead of low-cost organic waste materials like fruit peels.
- Limited research has focused on using fruit peel waste simultaneously for microalgal biomass production, PHA bioplastic synthesis, and biofertilizer generation in a single integrated bioprocess.
- Very few studies have evaluated the effective reuse of residual microalgal biomass after PHA extraction for improving soil fertility and plant growth, which is important for sustainable circular bioeconomy development.

The present study addresses these gaps by developing an integrated and sustainable waste valorization approach that combines fruit peel waste utilization, microalgal bioplastic production, and biofertilizer generation within a single eco-friendly biorefinery system.

Hypothesis

- Fruit peel waste contains sufficient organic carbon, sugars, and nutrients to support the efficient growth of *Chlorella* and *Spirulina* as an alternative low-cost culture substrate.
- Optimization of cultivation conditions, including pH, temperature, light intensity, photoperiod, and nutrient concentration, will significantly enhance microalgal biomass productivity and intracellular accumulation of polyhydroxyalkanoates (PHA).
- Solvent-based extraction methods will enable efficient recovery of biodegradable PHA bioplastics with detectable functional groups and structural characteristics confirmed through FTIR analysis.
- The residual biomass remaining after PHA extraction will retain valuable nutrients and bioactive compounds capable of promoting plant growth and improving soil fertility when applied as a biofertilizer.

Therefore, the study hypothesizes that an integrated microalgal bioprocess can effectively convert fruit peel waste into valuable bioplastics and sustainable agricultural inputs while supporting environmentally friendly waste management and circular bioeconomy principles.

Proposed Methodology

The present study aims to develop an integrated bioprocessing strategy for the valorization of fruit peel waste through microalgal cultivation and biopolymer production. Fruit peel waste will be pretreated and utilized as a nutrient-rich substrate for the cultivation of *Chlorella* and *Spirulina* under controlled laboratory conditions. Optimization of microalgal growth parameters, including pH, temperature, light intensity, photoperiod, and nutrient concentration, will be carried out to enhance biomass productivity and intracellular accumulation of polyhydroxyalkanoates (PHA).

The produced microalgal biomass will subsequently undergo solvent-based extraction and purification processes for the recovery of PHA bioplastics, followed by physicochemical characterization using analytical techniques such as FTIR. Furthermore, the residual biomass generated after biopolymer extraction will be evaluated for its nutrient composition and biofertilizer potential through plant growth promotion assays and soil fertility studies.

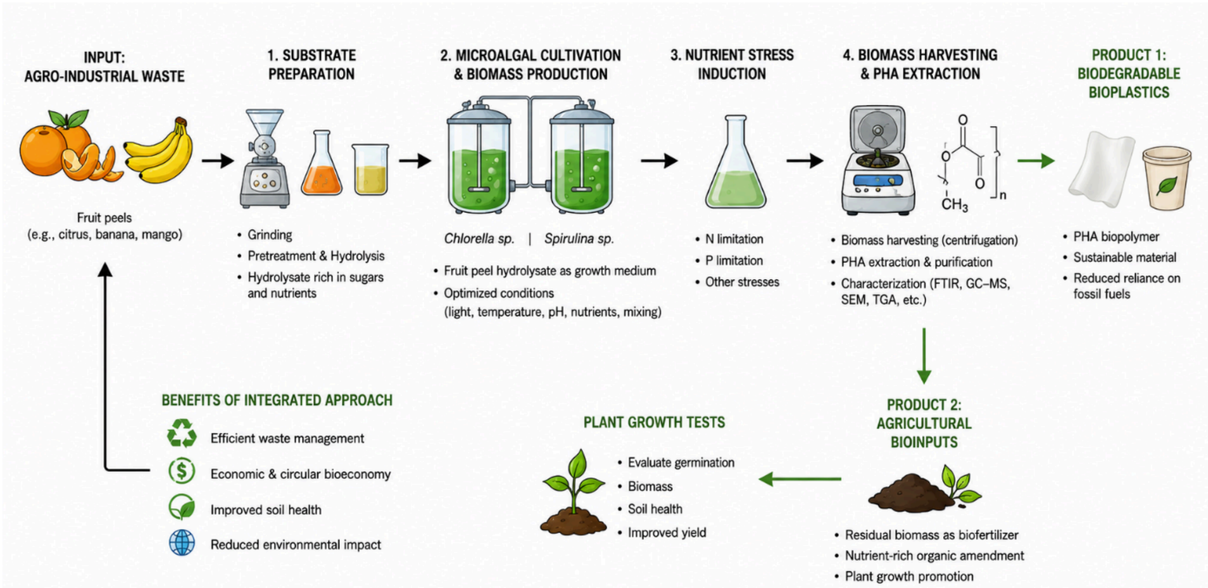

Figure 2. Proposed Integrated Biorefinery Model: Fruit Peel Waste to Bioplastics and Biofertilizers

This integrated methodology supports sustainable waste management, value-added bioproduct generation, and circular bioeconomy development.

Conclusion

The present review highlights the significant potential of microalgae-based bioprocessing for the sustainable utilization of fruit peel waste and the production of eco-friendly bioplastics. Fruit peel waste, being rich in organic nutrients and carbohydrates, can serve as an effective low-cost substrate for the cultivation of microalgae such as *Chlorella* and *Spirulina*. The integration of waste valorization with microalgal biomass production offers an environmentally sustainable approach for reducing organic waste while generating valuable bioproducts.

The review also demonstrates that optimization of cultivation conditions can enhance biomass productivity and intracellular accumulation of polyhydroxyalkanoates (PHA), which are promising biodegradable alternatives to conventional plastics. In addition, the residual biomass generated after PHA extraction possesses potential applications as a biofertilizer due to its nutrient-rich composition. Overall, this integrated biorefinery approach supports circular bioeconomy principles by converting agricultural waste into value-added products, promoting sustainable waste management, reducing environmental pollution, and contributing to green biotechnology and sustainable development.

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