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Banana Peel Waste as A Renewable Source of Valuable Phenolic Compounds: Bioconversion, Green Processing, Kinetics and Potential Applications: A Review

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ABSTRACT
Banana peel is an abundant agro-industrial residue generated during domestic consumption, food processing and commercial handling. Although commonly treated as waste, banana peel contains carbohydrates, dietary fibre, minerals, phenolic acids, flavonoids and other antioxidant compounds. The phenolic fraction makes banana peel a potential renewable feedstock for the recovery and production of higher-value chemicals. Hydroxycinnamic acids, particularly ferulic acid, can serve as precursors for the production of aromatic compounds such as vanillin. This review examines the chemical composition of banana peel, the occurrence and recovery of phenolic compounds, physical and chemical pretreatment methods, solvent and assisted extraction, alkaline hydrolysis, microbial and enzymatic bioconversion, factors affecting conversion, kinetic considerations, green chemistry principles, antimicrobial and antifungal potential, and possible applications of banana peel-derived products. Particular attention is given to the conversion of plant-derived aromatic compounds through microbial and enzymatic pathways and to the kinetic principles that can be applied in evaluating such processes. The review also discusses the challenges associated with substrate variability, pretreatment, inhibitor formation, product recovery and process scale-up. Future research should focus on integrated biorefinery approaches that combine selective extraction, hydrolysis, biological conversion and efficient product recovery to improve the economic and environmental sustainability of banana peel valorisation.

Keywords: Banana Peel; Phenolic Compounds; Vanillin; Green Chemistry; Kinetics; Agro-Industrial Waste

INTRODUCTION

The increasing generation of agricultural and food-processing residues has created significant environmental and economic challenges. At the same time, these residues contain organic compounds that can serve as renewable feedstocks for the production of chemicals, fuels, materials and other value-added products. The conversion of food waste into useful products is therefore an important component of the emerging circular bioeconomy (Lin et al., 2013; Mirabella et al., 2014; Sagar et al., 2018).

Banana is one of the most widely consumed fruits in the world, and its processing and consumption generate substantial quantities of peel. Banana peel has traditionally been regarded as a low-value waste material despite containing carbohydrates, fibre, minerals, phenolic compounds and other bioactive constituents (Anhwange et al., 2009; Mohapatra et al., 2010; Vu et al., 2018). The composition of banana peel varies with cultivar, maturity, geographical origin and processing conditions. This variation can influence the recovery of phenolic compounds and the efficiency of subsequent conversion processes.

Phenolic compounds are particularly important because of their antioxidant, antimicrobial and other biological properties. Banana peel contains several phenolic acids and flavonoids, with hydroxycinnamic acids representing an important group of compounds of interest for chemical and biotechnological applications (González-Montelongo et al., 2010; Vu et al., 2018). Ferulic acid is especially significant because it is a renewable aromatic precursor that can be converted into vanillin and other value-added compounds through chemical, enzymatic or microbial routes (Rosazza et al., 1995; Priefert et al., 2001).

The valorisation of banana peel therefore offers an opportunity to combine waste reduction with the production of useful chemicals. Green extraction techniques, hydrolysis and biological conversion can be integrated to recover target compounds while reducing the environmental impact associated with conventional processing (Chemat et al., 2012; Chemat et al., 2017; Saini et al., 2019).

This review discusses banana peel as a renewable source of phenolic compounds, with particular emphasis on ferulic acid, bioconversion to aromatic products, kinetic considerations and potential applications. The review also considers the challenges that must be addressed before laboratory-scale processes can be translated into economically viable industrial operations.

Banana Peel as an Agro-industrial Residue

Banana peel constitutes a significant proportion of the total banana fruit mass and is generated in large quantities during household consumption, food processing and commercial preparation. Its chemical composition includes carbohydrates, cellulose, hemicellulose, lignin, pectin, minerals, proteins, lipids and phenolic compounds (Anhwange et al., 2009; Mohapatra et al., 2010).

The composition of banana peel is affected by cultivar, maturity, geographical location and post-harvest handling. Consequently, the concentration of individual phenolic

compounds may differ considerably among samples. Such variability is important when banana peel is considered as a feedstock for biorefinery operations because the chemical composition of the starting material directly affects extraction yield and subsequent conversion efficiency (Vu et al., 2018; Wani & Dhanya, 2025).

Rather than treating banana peel exclusively as waste, it can be considered a renewable biomass resource. A biorefinery approach may involve sequential recovery of valuable compounds, followed by conversion of the remaining biomass into additional products. Such integrated approaches can improve resource efficiency and reduce the environmental burden associated with food waste disposal (Lin et al., 2013; Mirabella et al., 2014; Pathak et al., 2017).

Recent studies have further highlighted the potential of banana and plantain residues within circular bioeconomy systems, including their use as sources of bioactive compounds, fermentation substrates, adsorbents, carbonaceous materials and other value-added products (El Barnossi et al., 2021; Eixenberger et al., 2022; Santiago et al., 2022).

Phenolic Compounds in Banana Peel

Phenolic compounds are secondary plant metabolites characterised by one or more hydroxyl groups attached to aromatic rings. They include phenolic acids, flavonoids, tannins and related compounds. Their occurrence in banana peel contributes to the antioxidant and antimicrobial properties reported for banana peel extracts (González-Montelongo et al., 2010; Shahidi & Ambigaipalan, 2015).

The phenolic constituents of banana peel may occur in both free and bound forms. Bound phenolics can be associated with cell-wall components and may therefore require hydrolysis or other pretreatment methods before efficient recovery. The selection of extraction conditions consequently has a major effect on the amount and composition of phenolics recovered.

The extraction of phenolic compounds is influenced by solvent polarity, temperature, extraction time, solid-to-liquid ratio, particle size and pH. Conventional solvent extraction remains widely used, but newer approaches such as ultrasound-assisted and microwave-assisted extraction can improve mass transfer and reduce extraction time and solvent consumption (Azmir et al., 2013; Chemat et al., 2017; Vuong et al., 2019).

The antioxidant properties of banana peel extracts have been associated with their phenolic constituents. González-Montelongo et al. (2010) demonstrated that extraction conditions influence both the antioxidant activity and phenolic composition of banana peel extracts. These findings support the importance of optimising extraction procedures according to the intended downstream application.

Ferulic Acid as A Renewable Aromatic Precursor

Ferulic acid is a hydroxycinnamic acid widely distributed in plant biomass. It may occur in free form or be esterified or otherwise associated with cell-wall polymers. Because of its aromatic structure and renewable origin, ferulic acid has attracted considerable interest as a substrate for the production of value-added aromatic compounds (Rosazza et al., 1995).

Biotechnological conversion of ferulic acid can produce compounds such as vanillic acid, vanillin and related aromatic metabolites. Microorganisms capable of utilising ferulic acid have been studied extensively, and several biochemical pathways involved in its degradation and transformation have been characterised (Overhage et al., 1999; Overhage et al., 2003).

Vanillin is particularly important because it is widely used as a flavouring compound in the food industry and has applications in pharmaceutical, cosmetic and chemical formulations. Conventional vanillin production relies substantially on chemical synthesis, while biotechnological routes provide an alternative approach based on renewable substrates (Priefert et al., 2001; Kaur & Chakraborty, 2013; Banerjee & Chattopadhyay, 2019).

The conversion of ferulic acid to vanillin is therefore of particular interest in the valorisation of plant residues. However, the efficiency of the process depends on substrate availability, microorganism selection, metabolic pathway, reaction conditions and recovery of the product before further degradation occurs.

Recovery of Phenolic Compounds from Banana Peel

Physical Pretreatment

Physical pretreatment is commonly used to increase the surface area of biomass and improve contact between the substrate and extraction or hydrolysis medium. Drying, grinding and milling can reduce particle size and facilitate subsequent processing. However, excessive heating during drying may cause degradation or alteration of thermolabile phenolic compounds.

The choice of drying temperature and duration should therefore be considered in relation to the target compounds and intended processing route. Pretreatment should improve accessibility without causing unnecessary degradation of valuable constituents.

Solvent Extraction

Solvent extraction is one of the most common methods used to recover phenolic compounds from plant materials. Solvents such as water, ethanol, methanol and aqueous mixtures have been used because solvent polarity influences the solubility of different phenolic constituents (Dai & Mumper, 2010; Azmir et al., 2013). Food-compatible solvents, particularly ethanol-water mixtures, are attractive for applications involving food, pharmaceutical and cosmetic products. Solvent selection should consider extraction efficiency, toxicity, cost, solvent recovery and environmental impact.

Assisted Extraction

Assisted extraction methods have been developed to improve mass transfer and reduce processing time. Ultrasound-assisted extraction uses acoustic cavitation to disrupt plant tissues and facilitate the release of intracellular compounds. Microwave-assisted extraction uses electromagnetic energy to promote rapid heating and improve extraction efficiency (Chemat et al., 2017).

Microwave-assisted extraction has also been investigated specifically for the recovery of phenolic compounds from banana peel, demonstrating the potential of assisted techniques to improve recovery while reducing processing time (Vuong et al., 2019).

Alkaline Hydrolysis

Alkaline hydrolysis is particularly relevant when phenolic compounds are associated with cell-wall components. Alkaline treatment can disrupt ester linkages and improve the release of bound hydroxycinnamic acids. However, excessive alkaline treatment can result in degradation, oxidation or formation of undesirable products. Pretreatment conditions must therefore be selected carefully to maximise release of

target compounds while minimising degradation and inhibitor formation. The use of hydrolysis as part of an integrated biomass conversion process has been widely investigated for lignocellulosic materials (Alvira et al., 2010; Sun & Cheng, 2002).

Bioconversion of Plant-Derived Aromatic Compounds

Bioconversion refers to the use of biological systems, including microorganisms or enzymes, to transform a substrate into a desired product. Compared with some conventional chemical routes, biological conversion can offer high selectivity under relatively mild reaction conditions.

Microbial conversion of ferulic acid and related aromatic compounds has been extensively studied. Microorganisms such as Pseudomonas species and engineered bacterial strains can transform ferulic acid through several metabolic pathways leading to vanillic acid, vanillin and other intermediates (Overhage et al., 1999; Overhage et al., 2003). The choice of microorganism is critical because different organisms possess different enzymatic systems and may metabolise the desired product further. Metabolic engineering has consequently been used to redirect carbon flow towards desired aromatic products and reduce unwanted degradation (Barghini et al., 2007; Di Gioia et al., 2011).

Microbial Production of Vanillin

Vanillin production through microbial systems has attracted considerable interest because of the demand for naturally derived flavouring compounds. Ferulic acid, which can be obtained from plant biomass, is an important precursor for microbial vanillin production (Priefert et al., 2001; Kaur & Chakraborty, 2013). Several microorganisms have been investigated for vanillin production. These include bacteria, fungi and yeasts with different metabolic capabilities. The efficiency of conversion depends on the ability of the microorganism to transform the precursor to vanillin while limiting further oxidation or degradation of vanillin. Metabolic engineering has provided additional opportunities for improving vanillin production. Recombinant microorganisms can be designed to express enzymes involved in ferulic acid conversion while reducing competing metabolic pathways (Barghini et al., 2007; Di Gioia et al., 2011). Recent reviews have highlighted the continuing development of microbial vanillin production, including pathway engineering, selection of microbial hosts and optimisation of fermentation conditions (Banerjee & Chattopadhyay, 2019; Ma et al., 2022).

Enzymatic and Microbial Pathways

The conversion of ferulic acid into vanillin can involve several enzymatic steps. Depending on the microorganism, ferulic acid may undergo CoA-dependent or CoA-independent transformations. Enzymes such as feruloyl-CoA synthetase, enoyl-CoA hydratase/aldolase and related oxidative enzymes have been associated with different routes of aromatic compound metabolism (Overhage et al., 1999; Overhage et al., 2003).

The biochemical pathway selected by a microorganism determines the intermediates formed and the extent to which the desired product accumulates. In some systems, vanillin may be further converted to vanillic acid or other metabolites, reducing final product recovery.

Enzymatic conversion offers the possibility of high reaction selectivity. However, enzyme cost, stability, cofactor requirements and susceptibility to inhibition may limit direct industrial application. Microbial whole-cell systems can overcome some of these limitations by providing the required enzymatic machinery within the cell.

Factors Affecting Bioconversion

Substrate Concentration

Substrate concentration affects both reaction rate and product yield. At low concentrations, insufficient substrate may limit product formation. At high concentrations, substrate inhibition or toxicity may occur. The optimum substrate concentration is therefore dependent on the microorganism and pathway involved.

pH

pH affects microbial growth, enzyme activity, substrate solubility and transport across cell membranes. Each microorganism has a characteristic pH range within which growth and bioconversion are most efficient. Maintaining an appropriate pH is therefore essential for reproducible conversion.

Temperature

Temperature influences microbial growth, enzyme activity and chemical stability of the substrate and product. Increasing temperature generally increases reaction rates within a suitable range, but excessive temperature can cause enzyme denaturation, microbial stress or degradation of the desired product.

Oxygen Availability

Oxygen availability can influence oxidative and reductive steps in aromatic compound metabolism. The requirement for oxygen varies according to the microorganism and metabolic pathway. Aeration and agitation should therefore be controlled according to the physiological requirements of the selected organism.

Microbial Inoculum

The amount and physiological condition of the microbial inoculum influence the rate of substrate utilisation and product formation. An insufficient inoculum may result in a prolonged lag phase, whereas an excessive inoculum may cause rapid substrate depletion or competition for nutrients.

Product Inhibition

Accumulation of vanillin or other aromatic intermediates can inhibit microbial growth or interfere with enzymes involved in the conversion pathway. Product inhibition can reduce conversion efficiency and may necessitate strategies such as in situ product removal, adsorption or extraction.

Kinetic Considerations in Phenolic Bioconversion

Kinetic analysis provides a quantitative basis for evaluating the rate of substrate disappearance and product formation during phenolic bioconversion. Although biological systems can involve multiple simultaneous reactions, simple kinetic models can provide useful initial descriptions of conversion behaviour.

For a simple first-order reaction, the rate of disappearance of a substrate can be expressed as:

$$-\frac{d[S]}{dt} = k[S] \quad (1)$$

where [S] is the substrate concentration, t is time and k is the apparent first-order rate constant.

Integration of Equation (1) gives:

$$\ln\left(\frac{[S]_0}{[S]_t}\right) = kt \quad (2)$$

where $[S]_o$ is the initial substrate concentration and $[S]_t$ is the substrate concentration at time t.

Equation (2) can be rearranged into the linear form:

$$\ln[S]_t = \ln[S]_0 - kt \quad (3)$$

A plot of $\ln[S]_t$ against time can therefore be used to estimate the apparent rate constant when first-order behaviour is appropriate.

For product formation approaching a limiting concentration, a pseudo-first-order expression may be written as:

$$\ln(P_\infty - P_t) = \ln P_\infty - kt \quad (4)$$

where P_t represents product concentration at time t and $P\infty$ represents the limiting product concentration.

The effect of temperature on the apparent rate constant can be evaluated using the Arrhenius relationship:

$$k = Ae^{-E_a/(RT)} \quad (5)$$

where A is the pre-exponential factor, Ea is the activation energy, R is the gas constant and T is the absolute temperature.

Taking the natural logarithm of Equation (5) gives:

$$\ln k = \ln A - \frac{E_a}{RT} \quad (6)$$

A plot of ln k against 1/T gives a slope equal to −Ea/R. Consequently:

$$E_a = -R(\text{slope}) \quad (7)$$

These relationships should be applied with caution because microbial and enzymatic conversion systems may deviate from simple first-order behaviour. When substrate inhibition occurs, a Haldane-type model may provide a more appropriate description:

$$v = \frac{V_{\max}[S]}{K_s + [S] + \frac{[S]^2}{K_i}} \quad (8)$$

where v is the reaction rate, Vmax is the maximum reaction rate, [S] is substrate concentration, Ks is the substrate saturation constant and Ki is the substrate inhibition constant. Kinetic modelling can therefore assist in identifying rate-limiting stages, comparing processing conditions and predicting the behaviour of bioconversion systems during scale-up.

Green Chemistry and Banana Peel Valorisation

The valorisation of banana peel is consistent with several principles of green chemistry because it involves the conversion of an abundant waste material into useful products. The approach can reduce dependence on non-renewable raw materials and minimise waste generation. Green extraction emphasises the use of safer solvents, reduced energy consumption, improved extraction efficiency and the development of processes that minimise environmental impact (Chemat et al., 2012). Water and ethanol-based systems are particularly attractive where compatible with the target compounds and downstream application.

Biomass conversion can also be integrated into biorefinery systems in which several products are recovered from the same feedstock. Such approaches improve resource efficiency and can increase the economic viability of waste valorisation (Sheldon, 2014; Sagar et al., 2018).

Antimicrobial and Antifungal Potential

Phenolic compounds have attracted considerable attention because of their antimicrobial and antifungal properties. Their mechanisms of action may include disruption of microbial membranes, interaction with proteins and enzymes, alteration of cell permeability and interference with cellular metabolism (Cowan, 1999; Daglia, 2012). Banana peel extracts containing phenolic compounds may therefore have potential as sources of natural antimicrobial agents. However, activity depends on the composition and concentration of the extract, the extraction procedure, the target microorganism and the experimental conditions. The antimicrobial potential of plant-derived phenolics supports the possibility of developing banana peel-derived products for agricultural, food and other applications. Further work is required to establish activity, safety, stability and effectiveness under practical conditions.

Potential Applications of Banana Peel-Derived Products

Food and Flavour Industry

Phenolic extracts and aromatic compounds recovered from banana peel have potential applications in food formulations. Vanillin is particularly important as a flavouring compound, while phenolic extracts may provide antioxidant functionality.

Pharmaceutical and Cosmetic Applications

Phenolic compounds possess antioxidant and antimicrobial properties that may be useful in pharmaceutical and cosmetic formulations. However, safety, purity, stability and regulatory requirements must be established before commercial application.

Agricultural Applications

Banana peel-derived products may have potential applications in agriculture, including natural antimicrobial preparations, soil amendments and sources of bioactive compounds. Their use could contribute to the development of lower-waste agricultural systems.

Chemical Industry

Ferulic acid and related aromatic compounds can serve as renewable building blocks for the production of value-added chemicals. Biotechnological conversion provides an alternative route for producing selected aromatic compounds under relatively mild conditions (Rosazza et al., 1995; Priefert et al., 2001).

Materials and Energy Applications

After recovery of valuable compounds, residual banana peel biomass can be considered for other applications, including adsorbents, carbonaceous materials, biofuels and biocomposites. Integrated valorisation can improve overall resource utilisation (Yusuf et al., 2020; Eixenberger et al., 2022).

Challenges in Banana Peel Valorisation

Despite its potential, several challenges limit the large-scale valorisation of banana peel. These include variation in chemical composition, seasonal and geographical differences, moisture content, microbial deterioration and the cost of collection and transportation.

Pretreatment may also generate compounds that inhibit microorganisms used for subsequent fermentation. Detoxification may therefore be required before biological conversion, increasing processing complexity and cost (Mussatto & Roberto, 2004). Another challenge is the recovery and purification of target products from complex biomass-derived mixtures. Efficient downstream processing is essential because the economic viability of a bioconversion process depends not only on conversion yield but also on product recovery and purification.

Scale-up presents additional challenges because mixing, heat transfer, oxygen transfer and mass transfer may behave differently at larger volumes. Process optimisation must therefore consider both biological and engineering parameters.

Research Opportunities

Future research should focus on the development of integrated banana peel biorefineries in which different fractions are recovered sequentially. Selective extraction of phenolic compounds could be followed by hydrolysis of residual biomass and biological conversion of suitable aromatic precursors. The use of green extraction techniques should be further investigated to reduce solvent consumption and energy requirements. Ethanol-water systems, ultrasound-assisted extraction and microwave-assisted extraction represent promising approaches (Chemat et al., 2017; Vuong et al., 2019). Microbial and enzymatic systems should also be evaluated with respect to substrate tolerance, product inhibition, conversion selectivity and long-term stability. Metabolic engineering offers opportunities for increasing flux towards desired products while reducing competing pathways (Banerjee & Chattopadhyay, 2019; Ma et al., 2022).

Kinetic and process models can support optimisation and scale-up by providing quantitative information about substrate utilisation, product formation and temperature dependence. More detailed kinetic models may be required where multiple intermediates, inhibition and enzyme saturation occur. Life-cycle and techno-economic assessments are also needed to determine whether proposed banana peel valorisation routes provide meaningful environmental and economic benefits compared with conventional waste management.

CONCLUSION

Banana peel represents an abundant renewable biomass resource containing phenolic compounds and other constituents with significant potential for valorisation. Phenolic acids, particularly hydroxycinnamic acids such as ferulic acid, provide opportunities for the recovery and biological conversion of renewable aromatic compounds.

The integration of physical pretreatment, green extraction, hydrolysis and microbial or enzymatic conversion can provide a pathway for transforming banana peel from a low-value residue into a source of higher-value chemicals. Vanillin production from ferulic acid is one particularly promising example of such bioconversion.

However, differences in feedstock composition, pretreatment requirements, substrate and product inhibition, downstream recovery and process scale-up remain important challenges. Future research should therefore move towards integrated biorefinery systems supported by kinetic modelling, process optimisation, life-cycle assessment and techno-economic evaluation. Such approaches can improve the sustainability and practical application of banana peel valorisation while contributing to waste reduction and the circular bioeconomy.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY

No new datasets were generated or analysed in this review.

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