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AN OVERVIEW ON THERMOCHEMICAL VALORIZATION OF POTATO PEELS INTO ADDED-VALUE PRODUCTS

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ABSTRACT

The management of agri-food waste is a major environmental and economic challenge. Potato peels are a significant by-product of the food industry. They are rich in dietary fiber, phenolic compounds, residual starch, vitamins, and minerals. Valorization of potato peels into value-added products is a promising solution. Biochar and bio-oil can be produced via pyrolysis and hydrothermal carbonization. Hydrothermal carbonization converts wet biomass into hydrochar under moderate temperature and pressure, while pyrolysis decomposes peels in the absence of oxygen into solids, liquids, and gases. Potato peel biochar enhances soil fertility, sequesters carbon, adsorbs pollutants, and reduces greenhouse gas emissions. Chemical analyses confirm high nutrient and phenolic content with trace heavy metals, ensuring safety and efficiency. Overall, these treatments transform potato peel waste into renewable resources, supporting circular economy practices and climate change mitigation.

INTRODUCTION

Efficient waste management is one of the most important environmental challenges humanities faces today. Technological progress, economic development, urbanization, population growth, and consumption habits have significantly contributed to a rapid increase in waste generation. The highest amount of waste, around 44 % of the total global waste, derives from food and green waste (Kaza et al., 2018). According to a report by the United Nations Environment Programme (UNEP), in 2022, approximately 1.05 billion tons of food were wasted worldwide, equivalent to 19 % of total food production. It is distributed as follows: 60 % from households, 28 % from the food service sector, and 12 % from retail (Harvey, 2024). On average, each person annually discharges around 79 kilograms of food (FAO, 2019). The main reason for food loss and waste is the rapid growth of the global population and food consumption behaviour (Yukesh Kannah et al., 2020). Food waste contributes 8–10 % to global greenhouse gas emissions, mainly due to methane released during the food decomposition in landfills (He et al., 2019). Latin America and Europe have the highest consumer waste, with 200 and 180 kg per capita per year, respectively. North America and Oceania, North Africa, and Western and Central Asia generate 175 kg of consumer waste per capita annually. These are followed by consumer waste in industrialized Asia (155 kg), Sub-Saharan Africa (150 kg), and South and Southeast Asia (110 kg) per capita per year (Yukesh Kannah et al., 2020). Globally, annual food waste is generated mainly by cereals (around 30 %), roots, fruits, and vegetables (40–50 %), and oilseeds (about 20 %).

Potato peels are rich in dietary fibres (about 40–50 %), phenolic compounds, residual starch, vitamins, and minerals. Globally, the amount of potato peels generated is estimated at about 70,000 to 140,000 tons per year (Barampouti et al., 2023), and only part of the potato waste can be used as low-value-added animal feed or as biomass for biogas and energy production.

The valorisation of potato peels represents a significant opportunity to promote the circular economy and reduce the environmental impact of agri-food waste. The production of biochar is one of the methods of valorising this waste (Vescovo et al., 2025). The use of potato peels as raw material for valorisation is motivated by the desire to combine sustainability with innovation: this waste is abundant, constantly generated in the food industry, and its valorisation potential remains underexploited.

TRANSFORMATION AND VALORIZATION OF POTATO PEELS

The choice of valorisation disposal process depends on the properties of the raw material and the treatment objectives.

Hydrothermal Carbonization (HTC) is a thermochemical process that converts wet biomass into hydrochar (a carbon-rich biochar) by heating it in the presence of water, at temperatures of 180–250 °C and autogenous pressure, without requiring pre-drying (Petrović et al., 2024). It mimics the natural formation of lignite, but within hours instead of geological timescales, and can be applied to a wide range of feedstocks, including agricultural residues, sewage sludge, algae, and food waste (Petrović et al., 2024). The chemical reactions that occur are: hydrolysis-decomposition of chemical bonds by adding water; dehydration-removal of water from organic compounds; decarboxylation-removal of carboxyl (-COOH) groups; aromatization-formation of aromatic structures; condensation-formation of larger compounds by combining smaller molecules (Petrović et al., 2024). The advantages include: direct processing of wet biomass, no prior drying being required, saving energy and time; high production yield; valuable products; reduction of greenhouse gas emissions.

Pyrolysis is the most promising thermochemical conversion technology, able of simultaneously producing gases, liquids, and solids. It involves high temperatures (300-900 °C), in the absence of oxygen (Kan et al., 2016). Today, pyrolysis plays a strategic role in energy and recycling, offering solutions for pollution reduction and secondary resource valorisation (Williams, 2013). Pyrolysis relies on breaking the chemical bonds of complex molecules (e.g., cellulose, lignin, synthetic polymers) by applying heat. The process takes place in several successive stages (Anca-Couce, 2016): heating and drying to remove water from raw material (up to 150 °C); primary decomposition for breaking chemical bonds (200–500 °C); product formation to stabilize the new compounds and separate into gaseous, liquid, and solid fractions (above 500 °C). At lower temperatures, more solids (biochar) are obtained, while at higher temperatures gases dominate. Depending on operating parameters, pyrolysis can be classified as: slow pyrolysis – carried out at moderate temperatures (300–500 °C), with low heating rates, mainly producing biochar (Ronsse et al., 2013); fast pyrolysis – used to obtain pyrolytic oils; rapid heating, temperatures of 500–600 °C, short residence time (Venderbosch, 2019); flash pyrolysis – extremely rapid heating, high temperatures, for maximizing liquid yields (Ighalo et al., 2022).

Pyrolysis generates three main product types: solid fraction (coke or biochar), containing fixed carbon, ash, and mineral substances, used as an energy source, pollutant absorbent, or soil amendment (Sun et al., 2014); liquid fraction (pyrolytic oil) containing a mixture of hydrocarbons, oxygenated compounds, tars, and phenols, being refined and used as an alternative fuel or as raw material in the chemical industry (Sun et al., 2014); gaseous fraction (pyrolytic gas), containing H_2, methane, CO, and light hydrocarbons and having high energy value (Sun et al., 2014). Due to the closed reactor system used in pyrolysis, some compounds initially hydrolysed from biomass in the aqueous phase undergo condensation and polymerization reactions to form a secondary carbon layer (secondary carbon)~~.~~ Biogas is suitable as feedstock for hydrogen production, but also for replacing conventional products (Aktaş et al., 2009). Pyrolysis oil is a liquid fraction containing various organic compounds, such as hydrocarbons, alcohols, acids, and phenols. Its exact composition can vary depending on the feedstock used and pyrolysis conditions, and its properties can be adjusted by modifying these parameters (Xu et al., 2011).

Figure 1 shows a schematic flow of the valorisation process of agri-food waste through pyrolysis, with biochar as the main product.

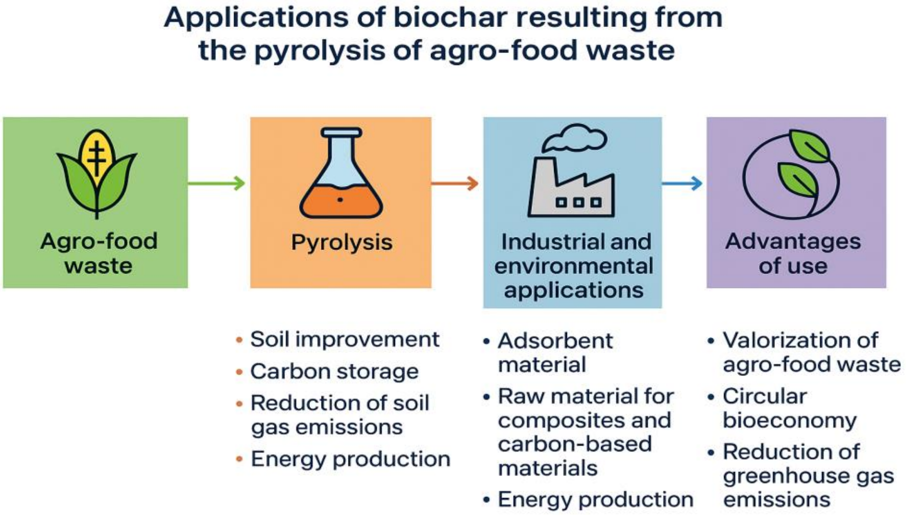

Figure 1. From waste to value-added product

Potato peels can be valorised through anaerobic fermentation processes to produce biogas, or through pyrolysis to obtain biochar and bio-oil as sources of renewable energy or as additives in agriculture and industry. Also, they be transformed into efficient adsorbents for the removal of heavy metals and dyes from wastewater (He et al., 2019).

Both biochar and compost can be used to improve soil properties, promote plant growth, and remediate contaminated soils. The porous structure of biochar obtained from potato peel pyrolysis is highly developed, enabling it to bind and stabilize water, various elements, and soil contaminants (Yu et al., 2019).

Biochar also has a liming effect when applied to acidic soils. The increase in soil pH resulting from biochar application has been widely studied in acidic soils. The hydrolysis of heavy metals with increasing pH leads to greater adsorption of heavy metals, thereby reducing their bioavailability in contaminated soils (Jing et al., 2020; Zhang et al., 2017).

Overall, biochar represents a sustainable solution for integrating the circular economy into the agri-food sector and mitigating climate change. To promote the commercialization of biochar for large-scale applications, a critical discussion is needed regarding the advantages and disadvantages of biochar for different applications from economic, environmental, and social perspectives.

ADVANCED METHODS FOR ASSESSING THE COMPOSITION OF POTATO PEELS WASTE

Any efficient waste valorisation process requires a thorough understanding of waste chemical and physical composition. This is highly variable and influenced by variety, pedoclimatic conditions, degree of maturity, or specific processing methods. A detailed analysis will allow not only the quantification of valuable components but also the identification of potential risks, such as the presence of heavy metals or toxic compounds, thus ensuring the safety of the final products (Aslam et al., 2024; Hidayat et al., 2024). (Aslam et al., 2024; Hidayat et al., 2024).

Table 1 correlates each class of compounds with the corresponding analytical techniques, creating a “conceptual map” of methodologies. Proximal composition, including moisture, proteins, lipids, fibres, and carbohydrates, is assessed using classical AOAC methods based on gravimetry, titrimetry, and extraction. Elemental composition (C, H, N, S, O) is determined through combustion followed by chromatographic quantification, while minerals and metals, both essential and toxic, are analysed using modern spectrometric techniques such as ICP-OES, ICP-MS, and F-AAS. Nonvolatile biochemical compounds, including polyphenols, glycoalkaloids, and fibres, are detected using spectrophotometry, HPLC, or LC-MS/MS, whereas volatile compounds, responsible for food aroma and flavour, are selectively extracted and analysed via HS-SPME or SBSE coupled with GC-MS. This structured overview provides a clear understanding of the relationship between compound type and the most suitable analytical approach.

Furthermore, the integration of these methods allows researchers to obtain both qualitative and quantitative information, supporting comprehensive food characterization. It also enables the identification of bioactive compounds with potential health benefits or toxicological concerns. The combination of classical and advanced techniques ensures accuracy, sensitivity, and reproducibility across diverse sample types. By linking compound classes to specific methodologies, Table 1 serves as a practical guide for selecting analytical strategies in food science, nutraceutical research, and quality control applications. Overall, this framework facilitates systematic study and comparison of complex food matrices.

Table 1.

Analytical Methods for Potato Peel Waste

Class of Compounds	Key Analytical Methods	Principle of the Method	Examples of Detected Compounds	References
Proximal Composition	Proximal Analysis (AOAC methods)	Gravimetry, titrimetry, extraction	Moisture, Ash, Proteins, Lipids, Fiber, Carbohydrates	(Cozma et al., 2024)
Basic Elements	Elemental Analysis	Combustion and quantification via gas chromatography	C, H, N, S, O	(Aslam et al., 2024; Cozma et al., 2024; Feist et al., 2008; Vandorou et al., 2024)
Minerals and Metals	ICP-OES, ICP-MS, F-AAS	Plasma emission and mass spectrometry	K, Ca, Fe, Zn, Pb, Cd, Hg	
Biochemical Compounds (Nonvolatile)	Spectrophotometry, HPLC, LC-MS/MS	Light absorption measurement, chromatographic separation, mass spectrometry	Polyphenols (quercetin, chlorogenic acids), Glycoalkaloids (α-solanine), Fibers (cellulose)	(Hidayat et al., 2024; Vescovo et al., 2025)
Volatile Compounds	HS-SPME, SBSE, GC-MS	Headspace microextraction, separation, mass spectrometry	Esters, Alcohols, Aldehydes, Terpenes, Ketones	(Grispoldi et al., 2022; Sarwar et al., 2025; Todea et al., 2014; Vasantha Rupasinghe & Kean, 2008)

The compositional analysis of potato peels (Table 2) highlights the presence of a wide spectrum of essential mineral elements and some heavy metals. Potassium is the most abundant mineral, followed by phosphorus, magnesium, and calcium, reflecting the nutritional potential of potato peels. Trace elements such as iron, zinc, and copper are also present, while the detection of heavy metals, including lead, cadmium, and chromium, underscores the importance of monitoring food safety. All elements were quantified using sensitive spectrometric techniques such as ICP-OES, ICP-MS, and AAS, ensuring accurate and reliable measurements. The presence of these minerals suggests that potato peels could serve as a valuable source of dietary micronutrients if properly processed. At the same time, the detectable levels of heavy metals indicate the need for careful assessment before their use in food or feed applications. Comparing the concentrations with established safety limits can help evaluate potential risks and benefits. Moreover, understanding the mineral profile contributes to exploring applications in nutraceuticals, functional foods, or as supplements. Overall, this analysis highlights both the nutritional potential and safety considerations associated with potato peel utilization.

Table 2.

Minerals and other metals in potato peels

Element	Potato peels (mg/100g)	Analytical technique	Reference
Potasium (K)	414	ICP-OES/ICP-MS	(Cozma et al., 2024; Vandorou et al., 2024)
Fosfor (P)	55.20	ICP-OES/ICP-MS	
Magneziu (Mg)	20.40	ICP-OES/ICP-MS	
Calciu (Ca)	6.76	ICP-OES/ICP-MS	
Fier (Fe)	1.03	ICP-OES/ICP-MS	
Zinc (Zn)	0.30	ICP-OES/ICP-MS	
Cupru (Cu)	0.05	ICP-OES/ICP-MS	
Plumb (Pb)	0.81	ICP-OES/AAS, ICP-MS	(Cozma et al., 2024; Todea et al., 2014)
Cadmiu (Cd)	2.07	ICP-OES/AAS, ICP-MS	
Crom (Cr)	0.60	ICP-OES/ICP-MS	

CONCLUSIONS

Potato peels represent a valuable agro-industrial by-product, rich in fibres, phenolics, starch, vitamins, and minerals, offering high potential for valorisation within the circular bioeconomy.

Thermochemical processes such as hydrothermal carbonization and pyrolysis provide efficient pathways to convert this waste into hydrochar, biochar, bio-oil, and syngas.

Biochar obtained from potato peels enhances soil fertility, improves water retention, sequesters carbon, and reduces greenhouse gas emissions, while also serving as an efficient adsorbent for pollutants. Its structural and chemical properties make it suitable for applications in soil remediation, energy production, and environmental protection.

Compositional analysis confirms a rich nutrient profile and relatively low concentrations of heavy metals, supporting safe agricultural use. Advanced analytical techniques allow precise characterization, ensuring efficiency and safety of valorisation processes.

Overall, potato peels thermochemical conversion is technically feasible and environmentally beneficial, contributing to waste reduction, renewable energy generation, and climate change mitigation. Future research should focus on process optimization, scale-up, and integrated life-cycle assessments to strengthen the role of such biowaste valorisation in sustainable development.

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