

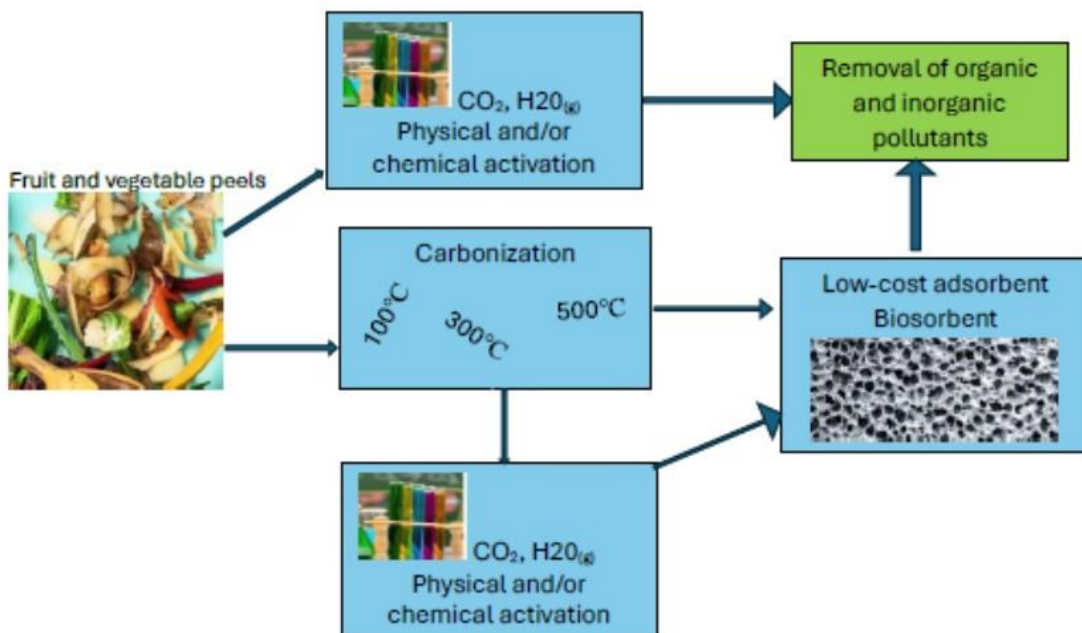
Fruit and Vegetable Peel Characteristics and their Conversion to Biosorbents using Hydrothermal Carbonization and Pyrolysis: A Review

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GRAPHICAL ABSTRACT



Fruit and Vegetable Peel Characteristics and their Conversion to Biosorbents using Hydrothermal Carbonization and Pyrolysis: A Review

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Peels make up a considerable proportion of solid waste generated from fruit and vegetable production and processing. If not properly managed, they could contribute to environmental degradation through the dispersion of nutrient-rich leachate and the release of various greenhouse gases. Alternatively, these peels could be transformed to biosorbents, which could assist in the removal of pollutants of environmental and human health concerns from wastewaters. Using peels as raw material for biosorbent production is an environmentally friendly and cost-effective option for waste disposal. Peels also contain bio-activators, which can be used to activate the biosorbent produced, minimizing the use of synthetic chemicals for biosorbent activation. This review considers the different physicochemical characteristics of vegetable and fruit peels that make them suitable raw materials for biosorbent production. Additionally, their transformation to biosorbents using hydrothermal carbonization and pyrolysis is discussed. The review concludes with a discussion on the efficiency of peel-based biosorbents in the removal of diverse types of pollutants from wastewater.

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Keywords: Hydrothermal carbonization; Low-cost adsorbent; Chemical activation; Pyrolysis; Bioactivators; Biochar

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INTRODUCTION

The complexity of chemicals contained in wastewater streams, coupled with poor management of industrial and domestic effluent discharges, have aggravated water pollution concerns globally. Both organic (dyes, phenols and benzene compounds, pesticides, fertilizers, hydrocarbons, detergents, oils, pharmaceutical, and personal care products) and inorganic pollutants (especially heavy metals) originating from untreated and partially and/or poorly treated wastewater are of environmental and human health concern because of their non-biodegradability, persistence, mutagenicity, toxicity, carcinogenicity, and teratogenicity (Bahadir *et al.* 2007; Georgieva *et al.* 2020; Kaur and Roy 2021; Goswami *et al.* 2022; Kumar and Kumar 2022). This concern is confounded by the fact that industries are increasingly making use of xenobiotics, which are not amenable to some of the available wastewater treatment methods. If these pollutants are allowed to reach water bodies, they could degrade their quality, aggravating the challenge of water

availability globally, especially in developing countries. The control and removal of these pollutants from effluents prior to their discharge into water bodies is therefore a matter of urgency to ensure environmental sustainability.

Despite the availability of multiple physical (sedimentation, skimming, coagulation, electrochemical), chemical (precipitation, oxidation, reverse osmosis, ion exchange, sorption), and biological (aerobic/anaerobic degradation) wastewater treatment methods with a potential to remove both organic and inorganic pollutants from wastewaters, their complete elimination from wastewaters has not always been possible. The increased volumes of wastewater generated, low efficiency of treatment methods, and the high cost associated with some of these methods are responsible for this failure (Ambaye *et al.* 2021). One of the wastewater treatment methods most commonly used in industry is adsorption, which relies on the surface chemistry of a solid material (adsorbent) to physically or chemically bind either organic or inorganic pollutants (adsorbate) from a solution (Dotto and McKay 2020; Bilal *et al.* 2021; Chai *et al.* 2021; Praveen *et al.* 2021; Kumar and Kumar 2022). Adsorbents used in the removal of pollutants from water include silica gel, zeolite, alumina, activated carbon, and nanocomposites, among others (Mishra *et al.* 2022).

Silica gel is a highly porous form of silicon dioxide produced from quartz sand or any silica rich material through hydrolysis or condensation reactions (Kazemzadeh *et al.* 2012; Visser 2018; Azmiyawati *et al.* 2019). Zeolites on the other hand comprise mainly of a framework of tetrahedra that may contain either silicon or aluminum (SiO_4 or AlO_4), and in which each oxygen atoms at the four edges of the tetrahedra are shared with adjacent tetrahedra (Derbe *et al.* 2021; Britannica 2024). The linking of a silica tetrahedron and an alumina tetrahedron creates a charge imbalance that is usually neutralized by the presence of an alkali or alkali earth metal (Rehákova *et al.* 2004). Zeolites may occur naturally, or they could be synthesized from glass materials, kaolin/metakaolin, coal fly ash, lithium slag, K-feldspar, and porcelain waste (He *et al.* 2016; Khaleque *et al.* 2020). The synthesis could be through alkali-fusion, sol gel, alkali leaching, or hydrothermal methods (Sugano *et al.* 2005; Wajima *et al.* 2008; Tsujiguchi *et al.* 2014; Shoppert *et al.* 2017). It is usually the synthesized zeolites, especially those synthesized from fly ash, that are used as adsorbents (Khaleque *et al.* 2020). Alumina, another commonly used adsorbent, is a whitish commercial adsorbent composed of aluminum oxide produced through either the Bayer process, sintering, hydrothermal synthesis, or sol-gel process (Banks and Bridgwater 2016). Alumina that is used as an adsorbent is usually activated (Rouquerol *et al.* 2014). Activated alumina is produced by dihydroxylation of aluminum hydroxide through calcination at temperatures of between 300 and 600 °C to create a highly porous structure with a high surface area (Banks and Bridgwater 2016). Activated carbon is one of the most popular adsorbents used in industry, and it is a highly porous, non-polar, amorphous material made from carbon rich materials such as bituminous and lignite, oil cake, and various biomaterials (Muttill *et al.* 2023). All these adsorbents are characterized by a high density of interconnected pores, and they therefore have large surface areas and high effective pore volumes (Pourhakkak *et al.* 2021).

The use of these adsorbents in wastewater treatment is however constrained by their cost, which make up about 70% of the overall cost of the adsorption process (Al-Ghouti and Da'ana 2020; Wang and Guo 2020). The cost of adsorbents varies depending on the raw materials used to produce them (Sarafray *et al.* 2019; Praveen *et al.* 2021), the

method used to activate the adsorbent (Sakhiya *et al.* 2021), the type of chemical used for activation (Kani *et al.* 2020), and adsorbent selectivity, degradation rate, and the operational costs of producing the adsorbent (Luo *et al.* 2019; Ahmad *et al.* 2020). The processing (grinding, mixing, filtering, heating) of the raw materials used for adsorbent production and the amount of adsorbate removed per unit area of adsorbent are also some methods used to determine the cost of adsorbents (Ighalo *et al.* 2022; GadelHak *et al.* 2023). Studies by GadelHak *et al.* (2023) have shown that energy and the raw material used to produce an adsorbent could each contribute up to 90% of the total cost of producing the adsorbent. Raw material and energy cost are influenced by the type and source of the raw material, and the country where the material originates or where the biosorbent is being produced (Ighalo *et al.* 2022). This is because countries vary in their level of inflation and cost of energy. Where energy is expensive, the cost of converting raw materials to biosorbents may be higher than in countries with lower energy costs. In countries where the inflation rate is high, raw materials are also likely to be more expensive than in countries with low inflation rates. These prohibitive costs have triggered research into the production of low-cost adsorbents.

Absorbents classified as low-cost adsorbents are usually made from materials that are renewable, inexpensive, eco-friendly, require minimal or simple processing before usage, and are available in large quantities (Renge *et al.* 2012). Examples of such materials are agricultural wastes, clay, bentonite, and montmorillonite. The use of clays, bentonite, and montmorillonite as adsorbents is however limited by their low adsorption capacity (Kainth *et al.* 2024). This has necessitated investigations into the potential of agricultural wastes as low-cost adsorbents. In a study by Yasir *et al.* (2023) it was shown that using bagasse fly ash or rice husk fly ash instead of commercial activated carbon to remove 2,4-dichlorophenol from paper and pulp mill effluent resulted in an annual saving of US\$6.33/m³ of water/year. This highlights the economic benefit of agricultural wastes as adsorbents. An analysis of the number of scientific articles published on Google Scholar in which investigations on the use of agricultural solid waste as adsorbents and as raw materials for adsorbent production are reported showed an increase from 1330 in 2012 to 263,000 in 2022. This increase highlights the growing interest in agricultural waste materials as low-cost adsorbents and raw materials from which such adsorbents can be produced.

Agricultural wastes with a potential to serve as adsorbents include fruit and vegetable wastes (FVW). World fruit and vegetable production has increased globally (Balali *et al.* 2020), with banana, durian, lemon, orange, potatoes and onions among the most widely consumed (Arias *et al.* 2022). Due to their high-water content, fruits and vegetables have a short shelf-life and therefore deteriorate within a short period of time when not well preserved. These spoiled fruits and vegetables together with their non-edible parts such as peels, pomace, seed, rind, residual stalks, straw, roots, leaves, and flowers comprise FVW. Peels are the outer covering or skin of a vegetable or fruit. According to Shakya and Agarwal (2019), Nguyen *et al.* (2022), Selvarajoo *et al.* (2022), Singh *et al.* (2022), and Manmeen *et al.* (2023), peels could contribute more than 50% of the overall weight of some fruit and vegetables, as shown in Table 1, depending on the peeling mode. Fruit and vegetable peels (FVPs) therefore comprise a significant fraction of agricultural solid waste. Kumar *et al.* (2020) and Rifna *et al.* (2023) reported that 90 to 92% of FVW are peels, while the remaining 8% is shared among seed, core, rag, stone, pods, vine, shell,

skin, and pomace, among other plant parts. These FVPs are generated in massive quantities globally in household kitchens and in vegetable and fruit-based industries.

Table 1. Peels Weight Percentage in Selected Fruits and Vegetables

Fruits/Vegetables	Estimated Peels Amount (wt%)	Fruit /Vegetable	Estimated Peels Amount (wt%)
Banana	30 to 40	Potato	15 to 40
Apple	5 to 15	Tomato	27
Mango	7 to 24	Pomelo	30
Pineapple	29 to 40	Durian	60
Orange	40 to 50	Lemon	40 to 50
Papaya	12	Mandarin	7 to 11

Modified after Shakya and Agarwal (2019), Nguyen *et al.* (2022), Selvarajoo *et al.* (2022), Singh *et al.* (2022) and Manmeen *et al.* (2023)

Joglekar *et al.* (2019), have reported that annual global fruit peel generation by countries follows the order China > USA > Philippines > India > Thailand > Malaysia, with approximate quantities of 35, 15, 8, 3, 2, and 1 million metric tons respectively. About 500 million tons of FVPs are produced by fruit and vegetable industries worldwide (Joglekar *et al.* 2019; Senit *et al.* 2019). They are therefore widely available and could be used as adsorbents or as raw materials for low-cost adsorbent production. Adsorbents produced from these plant-based materials as well as other biological materials are generally referred to as biosorbents. This review discusses the physico-chemical properties of both fruit and vegetable peels and biosorbents produced from them, the use of hydrothermal carbonization and pyrolysis to convert the peels to biosorbents, and the efficiency of the biosorbent produced from FVPs in the removal of pollutants from wastewater. The paper concludes with a discussion on the prospects of FVPs as biosorbents and raw materials to produce low-cost adsorbents.

FRUIT AND VEGETABLES PEELS AS BIOSORBENTS

FVPs contain various compounds and properties that make them capable of adsorbing various compounds. The authors' analyses of published articles on Google Scholar that investigated FVW as biosorbents between 2012 and 2022 indicate that 32% of these articles (8640 articles) used FVPs. A few of these studies used these peels as adsorbents in their natural state. Pathak *et al.* (2016), for example, investigated the potential of the peels of pineapple, pomegranate, watermelon, garlic, and green pea as adsorbents and found that the surfaces of these peels are characterized by both acidic and basic sites, though the acidic sites were dominant in many of the peels. The peels also had lower surface areas relative to those of commercial adsorbents, but they contained similar functional groups, such as phenol, alcohol, carboxylic acid, alkanes, amines, amino acids, and aromatic alkyl halides, which could adsorb various contaminants. In another study by Ng *et al.* (2016), using the natural peels of sponge gourd as a biosorbent, malachite green was successfully removed from wastewater. Singh *et al.* (2018) also used powdered banana peel to effectively remove rhodamine-B from water. Other reports on the use of FVPs as

adsorbents in their natural state are found in Reddy *et al.* (2015), Alvarez *et al.* (2018), Priyantha and Kotabewatta (2019), Ben-Ali (2021), Sánchez-Ponce *et al.* (2022), and Kainth *et al.* (2024). These studies all show that FVPs in their natural state have potential as adsorbents without having gone through any modification. However, when used as adsorbents in their natural state, they have low adsorption capacities (Yang and Jiang 2014; Olasehinde *et al.* 2018; Wattanakornsiri *et al.* 2022). They also have a high rate of biodegradation and could release soluble organic compounds, which may cause them to have low adsorption capacity, high chemical oxygen demand (COD), high biological oxygen demand (BOD), and high dissolved organic carbon (DOC) content (Wan Ngah and Hanafiah 2008; Adewuyi 2020; Kainth *et al.* 2024). Hence, chemically treated FVPs have also been investigated as biosorbents.

The most used method for the treatment of natural peels is the addition of a chemical to alter the surface properties of the peels. A few studies have reported on the methods and chemicals used in chemical treatment of FVPs in their natural state as well as the efficiency of the resulting adsorbents. Some of these studies and the methods used for treating the peels are presented in Table 2. Chemicals commonly used for treatment of these natural FVPs include H₂SO₄, FeCl₃.6H₂O, HNO₃, and NaOH (Table 2). The data in Table 2 also show that one type of peel could be treated using different chemicals and methods.

Table 2. Chemicals and Processes Used for the Treatment of Various FVPs in their Natural State

Fruit/Vegetable Peels	Description of Activation Process	Reference
Pomegranate	Pomegranate peels were rinsed with distilled water, oven-dried at 80 °C for 24 h, ground to a particle size of 250 to 500 μm, followed by addition of H ₂ SO ₄ . The peels were left in an oven for 24 h at 110 °C, then washed with boiled water, oven dried at 100 °C, and ground to a particle size of 250 μm.	Jawad <i>et al.</i> 2021
Pea	Peels were washed, oven-dried, crushed, 50% H ₂ SO ₄ added in a reflux system at room temperature followed by washing first with water then with ethanol.	El-Nemr <i>et al.</i> 2024b
Avocado	Peels were mixed vigorously with 80 mL of water for one hour, FeCl ₃ .6H ₂ O added and the mixture autoclaved at 180 °C for 12 h, then cooled, washed with water and methanol, and dried at 100 °C for 12 h.	Prabakaran <i>et al.</i> 2022
Tangerine	Peels were washed and dried at room temperature, milled to 250 μm and 0.25 M HNO ₃ added for 24 hours at room temperature. The peels were rinsed, dried at room temperature, and placed in 0.1M NaOH for 3 to 4 h, washed with distilled water, dried, and sieved.	Abdić <i>et al.</i> 2018
Dragon fruit Rambutan Passion fruit	Peels were washed with tap water, chopped, finely ground, dried in the sun for a week and in the oven at 60 °C for 24 h, powdered, washed with distilled water, sieved, 4 mol/L H ₂ SO ₄ added and stirred for 30 min. The treated peel was then filtered, washed, and dried in the oven at 60 °C for 24 h.	Wattanakornsiri <i>et al.</i> 2022

Orange	Orange peels were washed with distilled water, dried at 70 °C, crushed, soaked in ethanol and 1% NaOH at room temperature for 24 h, filtered, washed, and dries in a convection oven at 70 °C.	Liang <i>et al.</i> 2010
Apple Cucumber	Peels were washed, air dried at room temperature for 24 h, sliced and oven dried at 50 °C for 24 h, and ground to a particle size of 240 µm. 1.2 g of peel was then mixed with sodium alginate and dropped in CaCl ₂ solution at 4 °C for 24 hours, followed by washing and drying at 37 °C for 48 h.	Singh <i>et al.</i> 2019, 2021
Hamimelon Avocado Dragon fruit	Raw peels were washed, cut into pieces measuring about 0.04 cm ² , and saponified with 0.01M NaOH, after which they were washed and sonicated in 2 propanol. The mixture was then washed and dried.	Mallampati <i>et al.</i> 2015
Orange Pomelo Passion fruit	Raw peels were washed, cut into pieces measuring about 0.04cm ² , and saponified with 0.01 M NaOH, washed followed by sonication in 2 propanol. The peels were again washed and dried.	Nhung <i>et al.</i> 2018

With regards to the efficiency of chemically treated natural peel, Wattanakornsiri *et al.* (2022) used untreated peels of dragon fruit, rambutan, and passion fruit to remove Pb from water and found removal efficiencies of 76.6%, 49.6% and 84.7% respectively. The removal efficiencies were improved to 92.9%, 97.8% and 94.5% respectively for dragon fruit, rambutan, and passion fruit after treating them with 4 mol/L H₂SO₄ for 30 minutes. These researchers obtained similar improvements in efficiency with the same peels in the removal of Cd. Though chemical treatment improved the absorption capacities of the natural peels, their performance as adsorbents was not as good as the performance of their carbonized forms. In addition, the possibility of their degradation presents significant challenges to their use (Wattanakornsiri *et al.* 2022). Using natural peels of fruits and vegetables as raw material for adsorbent production instead of using them as biosorbents is therefore a more favored and widely researched use of FVPs. Among the FVPs that have been used as raw materials for the production of biosorbents are the peels of orange, banana, mango, avocado, mandarin, pineapple, tapioca, and litchi (Palma *et al.* 2016; Zhou *et al.* 2017; Shakya and Agarwal 2019; Wu *et al.* 2020; Qiao *et al.* 2021; Vigneshwaran *et al.* 2021a,b; Chen *et al.* 2022; Eleryan *et al.* 2022). The suitability of these peels as raw materials for biosorbents is determined by their physico-chemical properties, which dictate the surface characteristics and hence the sorption potential of the produced biosorbent.

PROPERTIES OF FVPs INFLUENCING THEIR SUITABILITY AS RAW MATERIALS FOR BIOSORBENTS

A plant's chemical composition is generally determined by its degree of maturation (Rahman *et al.* 2016; Sabuz *et al.* 2020; Quamruzzaman *et al.* 2022), genetic factors and the cultivation methods used to grow the plant (Indulekha *et al.* 2017; Güzel and Akpınar 2020; Widayanti *et al.* 2023), and the environmental conditions under which the plant is cultivated (Urban *et al.* 2007; Drobek *et al.* 2020; and Christopoulos and Ouzounidou 2021). Differences in these factors mean that the same plant species may

contain the same types of compounds and elements but in different concentrations because of the prevailing growth conditions. FVP properties of relevance to their potential as raw materials for biosorbent production are presented in Table 3 and discussed in the following sections.

Chemical Composition of FVPs

Like most plant parts, FVPs contain cellulose, hemicellulose, lignin, lipids, proteins, crude fiber, carbohydrate, alkaloids, hydroxides, carboxylic acids, alcohols, ketones, aldehydes, ether, and phenols, in amounts that vary with the type of fruit or vegetable (Table 3). These compounds contain polar functional groups and are rich in carbon (C) and oxygen (O). Carbon content in FVPs depends on the proportions of these compounds. Lignin has the highest ratio of carbon to oxygen (Demirbas 2003). Data presented in Table 3 show that all FVPs contain lignin, which contributes to a high amount of carbon. The rate of biodegradation of biosorbents with high C content would be slower, which can be explained by the content of lignin, which resists biodegradation. According to Pavlostathis (2011), lignin decomposition determines the rate at which lignocellulosic materials are biodegraded because of its high carbon and low nitrogen contents. Data presented in Table 3 indicate that FVPs contain C in the range of 39 to 52%, with mandarin peels having a higher amount of carbon compared to the other FVPs presented in Table 3. Biosorbents produced from mandarin peels may therefore be more stable than those from mango peels which have lower C content.

Oxygen is the primary element in many polar functional groups contained in compounds that are found in FVPs. These compounds contain both labile and recalcitrant O fractions, but the recalcitrant fraction is what is left in the biosorbent after carbonization of the peel (Tran *et al.* 2022; Viswanathan *et al.* 2023). FVPs contain a high amount of O, with concentration values ranging from 43 to 52.3% (Table 3). Durian peels have relatively lower O content than orange and lemon peels (Table 3). FVPs with high O content are likely to produce biosorbents with higher adsorption capacities because of the presence of many functional groups on the surface of the biosorbent. Nitrogen and sulfur, which are often associated with the formation of greenhouse gases are also present in all FVPs though in lower amounts compared to other elements (Table 3). Though not particularly important in peels used for biosorbents, they are important in peels used as feedstock for biochar designed for soil application.

Analyses of the elemental ratios in FVPs or any biomass provides some insight into their stability and degradability, polarity, and hydrophilicity (Hu *et al.* 2020; Wijitkosum 2022). High values of O/C and (O + N)/C respectively indicate a strong degree of hydrophilicity and polarity (Chen *et al.* 2016). FVPs are mechanically weaker than woody plants because they contain low amounts of lignin and are therefore easily biodegraded with consequences on their molecular structure (Abiodun *et al.* 2023). They are therefore not as stable as woody biomass and may not be reuseable, especially in their natural form (Fosso-Kankeu *et al.* 2014). Data presented in Fig 1 show that mango peels have weak aromaticity because of their high mean H/C values, whereas orange peels have the strongest aromaticity. According to Nzila (2018), aromatic compounds are more resistant to biodegradation than aliphatic compounds. Orange peel-based biosorbents are therefore likely to be more stable because of their higher aromaticity and slower rates of degradation compared to mango peel-based biosorbents.

Table 3. Chemical Composition of Selected Fruit and Vegetable Peel Biomass

Fruit/ Vegetable	Chemical substances contained in peels	Elements	Moisture content (%)	Ash content (%)	HHV (Mj/Kg)	Fixed Carbon (%)	Volatile Matter (%)	Total C (%)	Total H (%)	Total N (%)	Total O (%)	Total S (%)	Ref.
Apple	Phenolic, flavonoids, anthocyanins, antioxidants, vitamins, Vitamins, hemicellulose, lignin, cellulose	Na, K, Ca, Mg, Fe, Zn	3.64-8.7	1.9 - 2.14		1.37	87.40	43.63	7.43	0.63	48.30	-	(Hoseinzad eh <i>et al.</i> 2013; Feumba <i>et al.</i> 2016; Güzel and Akpınar 2020)
Banana	Steroids, phenolics, tannins, flavonoids, triterpenoids, Glycosides, carotenoids, ellagitannins, anthocyanins, vitamin C, essential oil, hemicellulose, lignin, cellulose	K, Ca, Na, Fe, Mn, C, O, N, Br, Rb, Sr, Zr and Nb,	6.8 -11.4	5.1 - 13.36	14.3- 18.89	0.43- 31.3	53.6- 83.1	39.9- 47	6.0-7.1	0.7-1.0	45.5- 52.28	-	(Kabenge <i>et al.</i> 2018; Lam <i>et al.</i> 2018; Pyar and Peh 2018; Selvarajoo <i>et al.</i> 2020)
Durian	Ethanol, cellulose, hemicellulose, lignin, fiber	Mg, Ca, P, S, Si, Fe, Na, Mn, C, N, O, Cu, Zn	3.45 - 11.2	4.20 - 5.86	13.8	17.1 – 21.65	69.4 – 74	40.1	5.5	-	43.8- 44.0	0.1	(Manmeen <i>et al.</i> 2023) (Adunphatc haraphon <i>et al.</i> 2020)
Lemon	Cellulose, hemicellulose, glucose, lignin	Na, S, Ca, C, N, O,	5.17 - 10.86	0.73 - 12.1	10.01- 26.3	4.81 - 29.83	23.98 - 80.8	43.1	5.8	0.9	50	0.01	(Abidi <i>et al.</i> 2023)
Mandarin	Polyphenols, antioxidants, carbohydrates, hemicellulose, lignin, cellulose	C, N, O,	5.2 - 9.3	1.8 - 8.3	17- 26.4	10 - 52	38 - 83	52.5	6.5	2.1	38.9	-	(García- Sánchez <i>et al.</i> 2016; Koyuncu and Güzel 2021)
Mango	Pectin, carotenoids, polyphenol, protein, lipid, crude fiber,	Ca, Mg, C, H, O, Na, K, Fe, Cu,	7.46 - 7.57	1.84 – 3.23	16.13	18.49	70.71	27.9	42.79 - 51.3	5.03 – 5.17	0.79- 2.61	0.27	(Sánchez- Camargo <i>et al.</i> 2019)

	hemicellulose, lignin, cellulose												
Orange	cellulose, hemicellulose, chlorophyll, pectin, lignin, pigments and other low-molecular weight hydrocarbon, essential oil	Fe, K, Na, Li, Ca and Ba, Zn, Mg, P, C, N, O,	1.6 -13.2	2.68-11.5	19.3	34.8-53.8	29.5 -50.9	42-48.8	3.09-6.0	0.5-1.42	46-51	0-0.13	(Kumar <i>et al.</i> 2018; Lam <i>et al.</i> 2018; Jawad <i>et al.</i> 2019; Ullah <i>et al.</i> 2023)
Pawpaw	hemicellulose, lignin, cellulose	Ca, Zn, Fe, Mn, C, N, H, O,	5	10.22									(C. Egbuonu <i>et al.</i> 2016; Pathak <i>et al.</i> 2016; Dahunsi <i>et al.</i> 2017; Suchiritha <i>et al.</i> 2017; Oladipo <i>et al.</i> 2020)
Pear	Flavonoids, Polyphenols, antioxidants, carbonyls, phenols		9.11	14.57									(Parafati <i>et al.</i> 2020)
Pineapple	hemicellulose, lignin, cellulose	Ca, Zn, Fe, Mn, O, C, N, H,	6.78 -8.86	3.13 -6.55	19.09	0.83 –19.52	68.96 -83.8	45.7 -47.4	6.1 -6.5	0.53-1.08	40.64 -47.2	-	(Pathak <i>et al.</i> 2016) (Hu <i>et al.</i> 2020)
Pomegranate	Alcohol, phenolic, carboxylic, alkane	C, K, Fe, K, N	8.92 -10.43	3.17 -4.0	14.61	0.25-25.4	62.5-85.7	44.5	5.28		18.29	-	(Ullah <i>et al.</i> 2012; Jalal 2018; Kafeel <i>et al.</i> 2023)
Butternut	Antioxidants, phenols, hemicellulose,	C, N, O,		8 -20	16.4-25.0	10 -42	38 -78.8						(Martínez <i>et al.</i> 2021)

	lignin, cellulose												
Tomatoes	Fiber, cellulose, hemicellulose, lignin, antioxidants, phenolics	Ca, Mg, K, Zn, Fe, Na, C, O, N,	4.67 - 10.26	3.01 - 4.87	22.50	12.34	78.12	61.4 - 55	7.9 - 8.7	1.8 - 2.8	25.9 - 34	0.3	(Brachi <i>et al.</i> 2016)
Potato	polyphenols, phenolic acids, lipids, pigments, lignin, dietary fibers, fatty acids, minerals, vitamins, protein, cellulose, hemicellulose, lignin.	K, Mg, Ca, Fe, Zn, B, Mn, C, Cu, O, N,	8.31 - 8.97	0.8 - 8.60	19.6	5.15 - 56.3	66.5- 89.4	43.9- 46.7	5.80- 6.47	0.4- 3.37	46.8	0.15	(Liang <i>et al.</i> 2015; Sepelev and Galoburda 2015; Vaitkevičienė 2019; Daimary <i>et al.</i> 2022)
Pumpkin	Polyphenols, carotenoids, pectin, lutein, zeaxanthin, vitamin E, ascorbic acid, phytosterols, selenium, linoleic acid	C, H, N, S,	5.96 - 75.68	0.41 - 10.65		39.2	52.8						(Hussain <i>et al.</i> 2022)

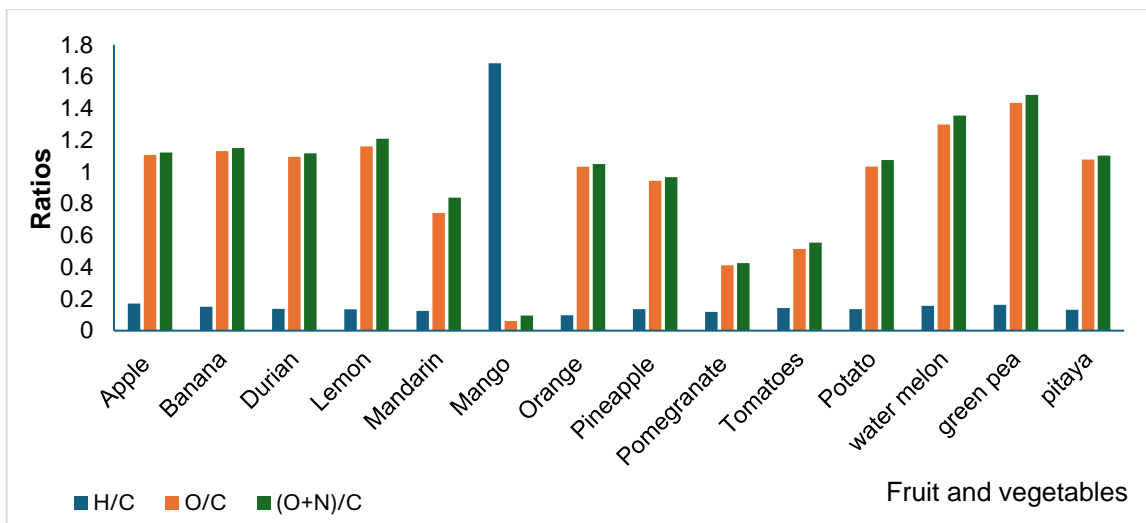


Fig. 1. Elemental ratios of various fruit and vegetable peels

The values for both O/C and (O + N)/C ratios, which are all close to unity, are similar for each peel (Fig 1) and indicate that most FVPs are hydrophilic and can interact with water. Biosorbents produced using FVPs as raw material may therefore be relatively stable, especially if modified, and their increased ability to interact with water could increase their efficiency as adsorbents for the removal of pollutants in water because of increased contact with the adsorbate of interest.

Proximate Characteristics of FVPs

Proximate analyses of peels evaluate the moisture, volatile matter, fixed carbon, and ash contents in the peels in an endeavor to appraise biosorbent yield from the peels and the amount of energy required to thermally convert the peels to biosorbent (Tillman *et al.* 2012; Ganogpichayagrai and Suksaard 2020). Proximate analyses are carried out to determine the portion of a material that burns in a solid (fixed carbon) and gaseous state (volatile matter), as well as the amount of inorganic material (ash) contained in the biomass (Nunes *et al.* 2018). In the case of FVPs, these analyses provide valuable information on the energy requirements if thermal processing is to be used to convert the peels to biosorbents. The moisture content in FVPs, for example, contributes to the energy required to transform them to adsorbents because it determines whether the peel will require a drying stage or not. According to Ponnusamy *et al.* (2020) and Selvarajoo *et al.* (2022), a biomass that has 15% or less of moisture can go through pyrolysis without being dried. High moisture content is also used as an index of microbial stability and susceptibility to microbial degradation of biomass. The higher the moisture content of the peel, the higher the rate of microbial degradation of the peel (Sadaf *et al.* 2022; Selvarajoo *et al.* 2022), and the shorter will be its shelf-life. High degradability of the peel could be desirable or not, depending on the type and stability of the metabolites that ensue from the biodegradation process. Some of the products of decomposition may be more stable than the fresh peel biomass or they may contain functional groups with high absorption capacities for various contaminants relative to the undegraded peel. This, however, needs further investigation. The highest and lowest moisture contents of the FVPs reported in Table 3 were 13.2% and 0.8% respectively for orange and potato peels. Based on the recommendation of Ponnusamy *et al.* (2020) and Selvarajoo *et al.* (2022), most FVPs may not need to be dried

prior to heat treatment because of the relatively low moisture content (< 15%). This reduces the cost of producing biosorbents from FVPs because the energy required for drying to reduce moisture content is eliminated.

Ash content is used as an indicator of the presence of inorganic matter or non-combustible material in biomass. High or low ash content in the biomass can be good or bad, depending on the intended use of the biosorbent produced from the peel. High ash contents in biomass may be desirable where there are intentions to recover elements from the ash because of the high concentrations of various elements including alkali and alkali earth metals, and heavy metals in biomass ash (Puri *et al.* 2024). Studies (Qiu *et al.* 2018; Nguyen *et al.* 2020; Xu *et al.* 2022) have also shown that the ash of some biomasses have good adsorption properties and have therefore been investigated as adsorbents. High ash content in biomass could therefore also be desirable if the ash is to be used as an adsorbent. However, low ash content is recommended for biomasses to be used to produce biosorbents. Li *et al.* (2017) have highlighted that high ash content may lower the efficiency of biosorbents because it could lead to blockage of pores, which will require chemical treatment to open. As shown in Table 3, the lowest ash content of 0.73% was found in mandarin peel and the highest (13.4%) in banana peels. Data presented in Table 3 and Fig. 2 show that fruit and vegetable peels have ash contents that are relatively low (< 20%) compared to those of other biomasses including rice husks, rice straw, wheat straw, or maize straw with ash contents of up to 29.4% (Wijitkosum 2022). The low ash content in the peel biomass is an indication that biosorbent yield when using FVPs is dependent mainly on the amount of fixed carbon. Fixed carbon in the peels comes mainly from the lignin and volatile matter content in the peels (Sharma *et al.* 2004), and an inverse relationship exists between fixed carbon and biosorbent yield. The fixed carbon content in peels is therefore also an important characteristic as far as its use in the production of biosorbent is concerned.

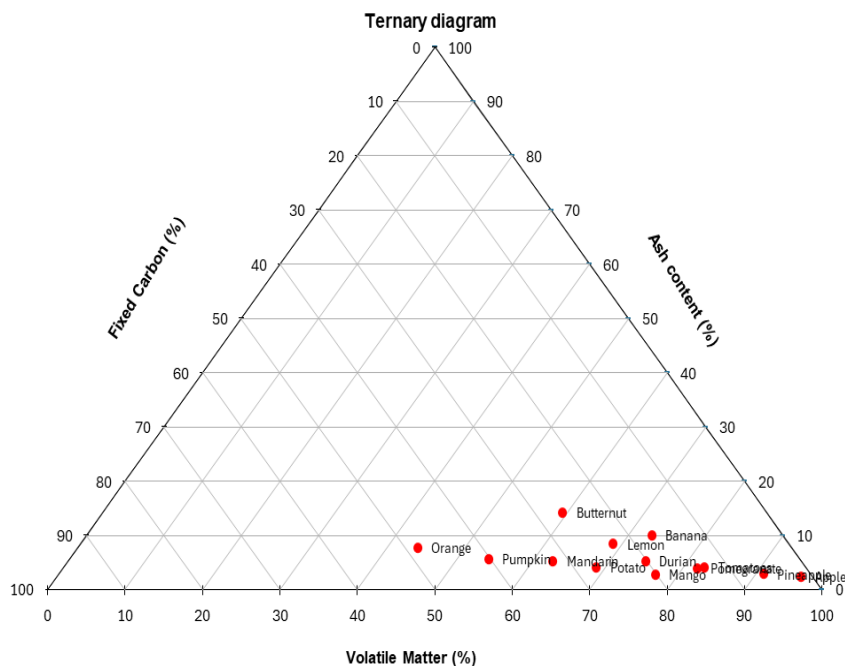


Fig. 2. Mean ash content, volatile matter content, and fixed carbon content in vegetable and fruit peels

Fruits and vegetable peels are also characterized by the presence of excessive amounts of volatile matter. The amount of volatile matter in fruit peels seems to be higher than what is contained in vegetable peels, but the fixed carbon content in vegetable peels are higher than in fruit peels (Table 3). There is a relationship between the fixed carbon content, ash contents, and volatile matter in biomasses. Most FVPs have their data points on the ternary plot in Fig. 2 concentrated in regions where the volatile matter is greater than 50%, the fixed carbon content is greater than 80%, and the ash content is below 20%.

Thermal Properties of Peels

Thermal treatment is the main method used to transform FVPs to biosorbents, and so it is essential that the peels possess good thermal properties. Higher heating value (HHV) refers to the amount of heat released by a completely dry unit mass or volume with an initial temperature of 25 °C once it is combusted and the products have returned to a temperature of 25 °C (Basu 2010). The HHV is used to report the thermal properties of biomass. Biomasses with relatively high HHV are easily processed during pyrolysis as compared to those with low HHV. The HHV of biomasses is influenced by their chemical composition, especially the amounts of C, N, S, O, H, volatile substances, fixed carbon, and ash contents (Esteves *et al.* 2023). Though these elements have been widely used to model the HHV of biomasses (Manatura *et al.* 2022), the content of lignin and the lipophilic extracts present in the biomass according to Raveendran and Ganesh (1996) and Esteves *et al.* (2023) determine the HHV of biomasses. Mangut *et al.* (2006) reported an HHV of 22.1 to 24.3 MJkg⁻¹ for tomatoes, whereas Kabenge *et al.* (2018) reported an HHV of 14.8 MJkg⁻¹ for banana peels. The HHVs of the FVPs presented in Table 3 are comparable with those of corn cob (18.7 MJ/kg), olive husk (19.9 MJ/kg), and hazelnut shell (19.3 MJ/kg) reported by Demirba and Demirba (2004), which are biomasses containing higher amounts of lignin than FVPs. From these values in addition to data presented in Table 3, vegetable peels seem to have higher HHVs than fruit peels and the HHVs of citrus fruit peels are higher than those of other fruit peels. The high HHV of citrus fruit peels could be associated with the higher content of aromatic oils in these peels relative to other peels. These oils increase the amount of volatile matter in the peels and consequently their calorific value. The relatively high HHV of FVPs indicates that the energy requirement for converting them to biosorbents through thermal treatment may be low.

Analyses of the properties of the FVPs indicate that they have varied properties, and the peels of oranges present favorable characteristics as a good raw material for biosorbent production. This may explain why many studies investigating fruit and vegetable peels as raw materials for biosorbents over the last 12 years have used orange peels (Fig 3).

The low moisture content and HHV of FVPs may reduce the amount of energy required to convert FVPs to biosorbents because drying to eliminate moisture is not necessary and they have good thermal properties which may also reduce the energy required for thermal treatment. The economic savings on energy when FVP-based biosorbents are used to remove pollutants from wastewater contribute towards lowering the overall cost of adsorption as a method of treating wastewaters (Mondal *et al.* 2016).

Though the factors which influence FVPs properties, especially environmental factors like temperature, salinity, and method of cultivation could be manipulated to obtain peels with desired properties, these manipulations may require time and effort. Transformation of the peels using other methods is a more favorable approach.

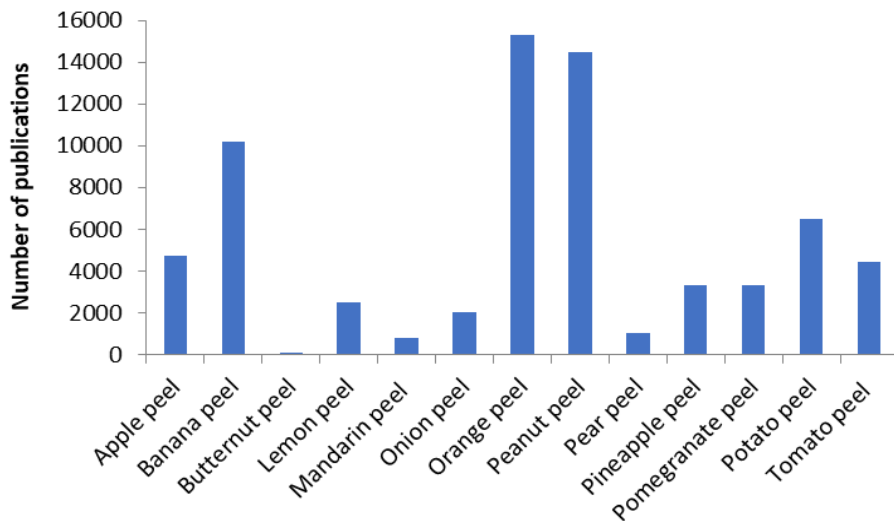


Fig. 3. Number of scientific publications on peels base biosorbent of selected fruits and vegetables in the last decade (Google Scholar)

TRANSFORMATION OF FVPS TO BIOSORBENTS

Pre-treatment of FVPs

Pretreatment of FVPs for biosorbent production could be as basic as separating them from other waste types, washing, drying, cutting, and grinding them (Rong *et al.* 2019; Meng *et al.* 2020), or it may involve more complicated processes, depending on the specific peel. A summary of the steps involved in peel pre-treatment is presented in Fig 4. FVPs are separated from other wastes, and then they are transported in plastic bags, coolers, or cardboard boxes with little consequence on their quality. Kainth *et al.* (2024) have mentioned the cost of transporting agricultural wastes as a constraint that could limit their use in biosorbent production despite their availability. However, compared to the cost of acquiring other adsorbents, which may sometimes be imported from other countries or mined from the earth, agricultural wastes still present an attractive economic option. Further to this, the disposal of FVW by the industries generating them may incur costs, which could be offset by selling these peels to industries where they can be recycled to biosorbents.

After transportation, the peels are then washed with tap water or solvents to remove dirt and sand particles (Zhao *et al.* 2018), followed by drying using either sunlight or an oven, or both to reduce energy consumption during drying (Zhao *et al.* 2018; Selvarajoo *et al.* 2022). Wherever moisture content exceeds 15%, Sial *et al.* (2019) and Sadaf *et al.* (2022) have recommended sun drying for one to 14 days combined with hot air oven-drying at a temperature range of 70 to 110 °C for 4 to 72 h to reduce moisture content to below 15% in peels. Once dried, the peels can be ground to further increase the surface area, especially if chemical treatment is required (Hu *et al.* 2021). Details of these steps are presented in Fig 4. Completion of all these processes renders the peel ready for treatment. The pre-treatment of FVPs is therefore simple and cheap with no need for any sophisticated instrument, which makes this type of biomass ideal as raw material for the production of low-cost adsorbents even in under-resourced places.

Treatment of FVPs Biomass

The transformation of FVPs could be done using bio-chemical, physico-chemical, or thermo-chemical methods (Fig. 4). In biochemical processing of peels, micro-organisms, or a biological catalyst (*i.e.* enzyme) is used to convert the peels to the desired product, whereas in thermochemical processing, heat and chemical reactions are used for the transformation of the peels (Tripathi *et al.* 2016).

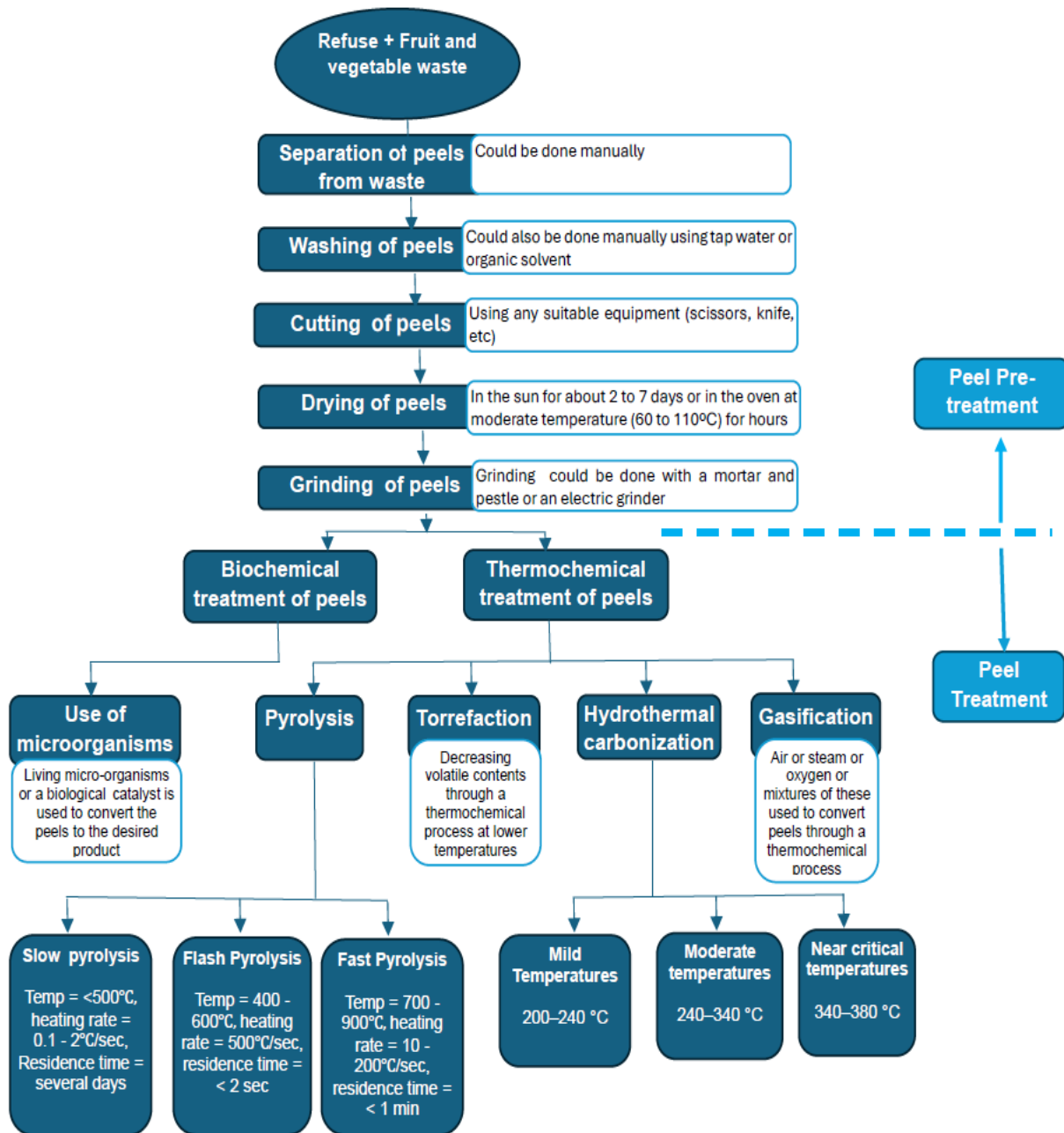


Fig. 4. Pretreatment steps and types of treatment used to convert FVPs to biosorbents

Thermal processes are widely used to transform most peels because multiple products (bio-oil, biochar, and gases) could be obtained through these processes, and they can transform various FVPs in record time (Wang *et al.* 2020). Thermo-chemical processes used to produce biosorbents from peels include gasification (He *et al.* 2022), torrefaction

(Lin *et al.* 2021), pyrolysis (Yu *et al.* 2017; Chen *et al.* 2022; Seow *et al.* 2022), and hydrothermal carbonization (Wu *et al.* 2020).

In gasification, either air, or water vapor, or oxygen, or some combination of them is used to convert peels into tar, char, gas, and ash (Guo *et al.* 2022). This process according to Mohan *et al.* (2014) is carried out under partial oxidation conditions, which convert some of the carbon contained in the peels to carbon dioxide (Goyal *et al.* 2008). Since not all the carbon in the peel is converted to a solid form, biosorbent yield is low when gasification is used in its production. Torrefaction, on the other hand, involves decreasing water and volatile contents in the peels at a relatively lower temperature (Tumuluru *et al.* 2021). It is sometimes described as high temperature drying because of the low temperatures used in the process. This relatively low temperature treatment is also likely to result in partial conversion of carbon in the peels. This review focuses on pyrolysis and hydrothermal carbonization because they are the most used transformation processes in the production of biosorbents from peels (Adeniyi *et al.* 2023).

HYDROTHERMAL CARBONIZATION

Hydrothermal carbonization (HTC) or wet pyrolysis converts peels into a high-carbon containing material (also called hydrochar) and solid fuels in an aqueous medium at temperatures and pressures ranging from 180 to 350 °C and 14 to 22 MPa, respectively, over several minutes (5 to 240 min). The processes involved during hydrothermal carbonization include hydrolysis, dehydration, decarboxylation, and aromatization in a low oxygen environment (Chen *et al.* 2017; Nizamuddin *et al.* 2017). Key aspects determining the quality of biosorbents produced through this process are the residence time, the temperature to which the peel is subjected, the pH, and the pressure under which the process takes place.

Factors Affecting Transformation of Peels by Hydrothermal Carbonization

Water

The aqueous medium commonly used in HTC is water, which is sometimes mixed with a small amount of either phosphoric or acetic acid. The water and acid release hydronium ions through auto-ionization, forming functional groups on the surface of the produced hydrochar (Zhou *et al.* 2022). Such treatment also helps in the separation of the products (hydrochar (20 to 80%), gas, and liquid) produced during the HTC process (González-Arias *et al.* 2022). The produced hydrochar is often dried in an oven to ensure complete exclusion of water molecules (Akkari *et al.* 2023). The use of water as a reaction medium during HTC means that peels are amenable to the HTC process, since they contain moisture. FVPs may therefore not need drying prior to their carbonization through HTC, which reduces the amount of energy required. Amer and Elwardany (2020) stated that the drying step of biosorbent production is the step with the highest energy consumption because of the high latent heat of water. Eliminating this step therefore reduces the energy required, and consequently the cost of producing biosorbents from FVPs using the HTC process (Funke and Ziegler 2010). Whereas too much moisture could affect HTC, too little moisture in the biomass could cause localized overheating and uneven temperature distribution with consequences on the quality of the hydrochar produced (Wang *et al.* 2019).

Temperature

Temperature remains the most important parameter in the HTC process, as it affects both the rate and the degree of decomposition of the lignocellulosic matter in the peels. Temperature regimes used in the HTC process are classified into mild, moderate, and near critical temperatures, with ranges as shown in Fig. 4. A reduction in the H/C and O/C ratios of the peels occurs with increase in hydrothermal temperature (Pradhan *et al.* 2020), resulting in an increase in aromaticity, stability, polarity, and oxygen containing functional groups in the hydrochar produced. At high HTC temperatures, polymerization of the peels increases and a decrease in volatile matter content occurs, but the end products are mostly gas (CO₂) and energy-rich hydrochar (Czerwińska *et al.* 2022). Lower temperatures are therefore more favorable for biosorbent production using HTC. Low HTC temperatures could however result in partial decomposition of peels and longer residence time in the reactor, whereas high HTC temperatures are linked to complete decomposition of the biomass within a shorter time (Nawaz and Kumar 2023) but low biosorbent and high fuel and gas yields from the peels. Where hemicellulose decomposition is targeted, it has been recommended that temperatures during HTC be kept between 150 and 230 °C because above 220 and 500 °C, respectively, cellulose and lignin decomposition are respectively more favored (Yu *et al.* 2023). The temperature range commonly used in HTC (Fig. 4) favors the transformation of FVPs to biosorbent because of their high hemicellulose and cellulose relative to lignin contents.

Residence time

The residence time of FVPs in the HTC chamber is determined by the type of peel and temperature used. A shorter than required residence time could lead to partial carbonization of the peel, whereas a longer than required residence time could result in waste of energy. A wide range of residence times (15 to 1080 minutes) have been used for the HTC process generally, but temperature has more effect on the yield of hydrochar than the residence time. This was shown by Chen *et al.* (2017), where 190 °C permitted 95% conversion of biomass, while only 56% conversion was obtained at 260 °C. They also revealed that a longer residence time at a lower temperature resulted in better hydrochar yield compared to higher temperatures and shorter residence times. Where yield is the target, lower temperatures are recommended. However, if biosorbent of superior quality is the target, then temperature plays a prominent role in the HTC process.

Pressure

The pressure under which HTC is carried out is self-determined by the carbonization temperature. High pressure in HTC is necessary to maintain water in its liquid form, since the process is carried out at temperatures above the boiling point of water (Chua *et al.* 2023). In the absence of pressure, the water would evaporate, compromising the entire carbonization process. The relevance of pressure, however, is dependent on the amounts of cellulose, hemicellulose, and lignin content of the peels. According to Güleç *et al.* (2021), peels with higher hemicellulose plus cellulose in their biomass structures are more affected by changing temperature and pressure than those with higher cellulose plus lignin. FVPs contain higher hemicellulose–cellulose structure, and so pressure may play a key role in their carbonization using HTC.

Though HTC consumes lower energy and produces less hazardous by-products, the resulting biosorbent is often less effective in the adsorption of pollutants and so there is always a need for chemical modification to enhance its adsorption capacity (Chen *et al.*

2017). The quality or efficiency of the resulting biosorbent also depends on whether the peel is fresh or dry. For example, chemically modified biosorbents produced from fresh peels using HTC were less effective in adsorbing Pb(II) ions compared to chemically modified biosorbents produced from pre-dried peels (Sitthisantikul *et al.* 2020; Zhou *et al.* 2022). Using HTC in the production of biosorbents from FVPs therefore needs further investigations, especially on the optimization of the process to improve the efficiency of the biosorbent while keeping the cost at a minimum.

PYROLYSIS

Pyrolysis is one of the oldest and most used processes for producing biosorbents from FVPs, and it involves thermal decomposition of the organic matter present in the peels in an atmosphere free from oxygen. Pyrolysis is controlled by different variables, including pre-treatment of biomass, particle size, pyrolysis temperature, pressure, heating rate, residence time, energy efficiency, and reactor design and configuration (Kan *et al.* 2016). During pyrolysis, evaporation of moisture and light volatiles occur between 0 and 200 °C, devolatilization and decomposition of hemicellulose and cellulose between 20 and 500 °C, and degradation of lignin and other compounds above 500 °C (Tomczyk *et al.* 2020). Depending on the temperature, heating rate, and residence time, pyrolysis is classified into slow, flash, and fast pyrolysis. Details of the temperature range, heating rate, and residence time of the biomass in the reactor during pyrolysis are presented in Fig. 4. Kan *et al.* (2016) and Gollakota *et al.* (2016) have also reported extensively on the different types of pyrolysis, and their article can be consulted for details of the process.

Factors Affecting Pyrolysis of FVPs

Temperature

Like with the HTC process, temperature plays a significant role in the quality of biosorbent produced from FVPs through pyrolysis. Lam *et al.* (2018) studied the effect of temperature on biochar made from orange and banana peels, and they found that biochar yield decreased from 75.3% and 55.6% at 300 °C to 32.8% and 30.7% at 500 °C, respectively, for banana and orange peels. These observations were confirmed, in terms of general trends, by Zhao *et al.* (2018) and Abdelaal *et al.* (2021) using different temperature ranges in the pyrolysis of orange and banana peels. The yield of biosorbents therefore decreases as the temperature of pyrolysis of FVPs increases. Considering that FVPs contain considerable amounts of cellulose and hemicellulose, which are pyrolyzed at temperatures below 500 °C, pyrolysis temperatures above 500 °C would result in charring of the peels. Slow pyrolysis is therefore mostly preferred in the production of biosorbents from FVPs. However, at temperatures of 300 °C and below, it has been observed that the carbonization of FVPs is incomplete, resulting in a mixture of peel biomass and biosorbent at the end of the process. The partial carbonization of the peels is likely to result in low surface area and porosity of biosorbents (Chen *et al.* 2012). The non-pyrolyzed compounds are usually mostly lignin and cellulose (Pelaez-Samaniego *et al.* 2022). These limitations present a drawback to the use of slow pyrolysis in the production of biosorbents from FVPs. At temperatures above 300 °C, a significant decomposition of FVPs is observed. Arampatzidou and Deliyanni (2016) prepared biochar from potato peels using slow pyrolysis (at 400 °C), flash pyrolysis (at 600 °C) and fast pyrolysis (at 800 °C). The results

revealed an increase in surface area and pore volume with increase in pyrolysis temperature. Studies carried out by Selvarajoo *et al.* (2020) on the effect of pyrolysis temperatures (300, 500, and 700 °C) on banana peel biochar indicated that the best biochar was obtained when pyrolyzed at 325 °C. Zhang *et al.* (2020b) also noticed an increase in ash contents (from 5.75% at 300 °C to 9.06% at 700 °C), pH (from 6.87 at 300 °C to 9.06 at 700 °C), and carbon content (from 51.3% at 300 °C to 78.6% at 700 °C) while studying the effect of the variation of pyrolysis temperature on mango peel-based biochar. They concluded that peel-based biochar produced at a pyrolysis temperature of 500 °C had the best surface properties. Based on the results from these studies, it is recommended that pyrolysis temperatures of between 325 and 500 °C be used to produce biosorbents from FVPs.

Energy requirement

Energy consumption is among the factors influencing the cost of producing adsorbents regardless of the ease with which the raw materials can be accessed and their availability. The amount of energy required to convert FVPs to biosorbents is influenced by their moisture content and HHV (Amer and Elwardany 2020). Where the peels have high moisture content, the moisture needs to be reduced through drying, which increases the energy requirement of producing the biosorbent. The moisture content of FVPs is however generally below 15% (Table 3), which may not require drying. The HHV of the FVPs also determines the amount of energy required to convert the peels to biosorbents. Vegetable peels present an advantage over fruit peels in this regard because of their higher HHV (Table 3). Even among the fruit peels, citrus fruit peels have an advantage because the aromatic oils contained in their peels increase their fuel value, with a consequent decrease in the amount of energy needed for carbonization. These aromatics also increase the volatile matter of these peels. In an endeavor to reduce the amount of energy used in the production of biosorbents from these peels, the volatile matter could be collected, cooled, and condensed to produce bio-oils and biogas (Amer and Elwardany 2020), which could be an additional source of energy. Alternatively, heat exchangers could be used to extract heat from smoke produced during a pyrolysis process, and the heat could be utilized for pre-drying of incoming biomass (Hubbe 2021). To make efficient the pyrolysis process while keeping the amount of energy required at a minimum, and the quality of biosorbent at an optimum, a catalyst could also be used.

A variety of catalysts including zeolite, silica, and biomass derived activated carbon are available as catalyst for biomass pyrolysis, but the choice of catalyst depends on the type of biomass to be pyrolyzed. Most studies on catalytic pyrolysis (Li *et al.* 2020; Poddar *et al.* 2022; Vignesh *et al.* 2022), however, indicate that catalysts are mostly used when biofuel production is the objective of pyrolysis and not when adsorbents are targeted. Rijo *et al.* (2023) however indicated that catalytic pyrolysis affects both bio-oil and biochar production depending on the catalyst. Further studies are needed to identify catalysts that could be used to enhance the yield of biosorbents from FVPs when slow pyrolysis is the only option.

Reactor conditions

A reactor is where the pyrolysis reactions take place. Several types of reactors have been developed, including the fluidized bed, fixed bed, and microwave reactors. A fluidized bed reactor is a heterogenous catalytic reactor in which a continuous flow of

heated high velocity upward flowing air lifts a layer of solid particles, bringing about fluidization, temperature stability, and extensive mixing of the particles (Brun-Graeppe *et al.* 2011). According to Nachenius *et al.* (2013), fluidized beds allow efficient transfer of heat to biomass and are commonly used with biomasses that have small particles. Fixed bed reactors are comprised of firebricks, steel, or concrete with a biomass feeding system, a gas exit, and an ash removal unit (Kurian *et al.* 2022). They are the most cost effective in the conversion of biomass into fuels (Makkawi 2014). In microwave reactors, heating of biomass occurs as a result of flipping of the orientation of the electric dipoles in the biomass (Deborah and Chung 2017). The advantages of microwave pyrolysis include good heat transfer, even distribution of heat throughout the biomass, versatility in terms of type of biomass that can be utilized, and ease of control of pyrolytic temperature (Wahi *et al.* 2017; Joo *et al.* 2021). Biosorbents produced through the microwave process also display better porosity and stability than biochar obtained from conventional pyrolysis (Wahi *et al.* 2017).

Fluidized bed, fixed bed, and microwave reactors are expensive reactors to acquire. In the fluidized bed reactor, energy is required to pump the gases in order to maintain fluidization and high circulation rates (Di Capua *et al.* 2015), which could increase the cost of producing a low-cost adsorbent. The choice of a reactor is often influenced by the desire to maximize energy (Liang *et al.* 2015; Uddin *et al.* 2018; Priyadharshini and Arvindhan 2024), and so less sophisticated and cheaper pyrolysis chambers have been used successfully. Most studies that have reported on the pyrolysis of FVPs including litchi, pumelo, pineapple, orange, and pitaya peels to produce biosorbents and biochars have made use of a muffle furnace (Fu *et al.* 2016; Wang *et al.* 2016; Wu *et al.* 2017; Lam *et al.* 2018; Hu *et al.* 2020; Zhang *et al.* 2020a) with reduced airflow to minimize oxygen in the chamber where nitrogen gas has not been available. Biosorbents produced from these improvised pyrolysis chambers have displayed favorable characteristics and high efficiency in the removal of both organic and inorganic pollutants from wastewater.

The treatment of FVPs to produce biosorbents therefore involves optimizing several aspects including temperature, residence time of biomass in reactor, and moisture content among others to obtain biosorbents with good adsorption potential. The optimization is likely to be peel dependent, since each FVP has distinct characteristics and chemical composition. In terms of quality of biosorbents produced, when carried out under optimum conditions, HTC produces biosorbents with better surface properties than pyrolysis. This statement is supported by the works of Chen *et al.* (2017), Sitthisantikul *et al.* (2020), and Yusuf *et al.* (2020). They attributed the better surface properties of the biosorbents produced through HTC process to the lower ash, alkali, and heavy metals content compared to biosorbents produced through pyrolysis. This is also evidenced by the results from studies carried out by Zhou *et al.* (2020), who used durian peel as feedstock in the production of hydrochar and biochar. The hydrochar had a higher surface area (1850 m²/g) compared to the biochar (1810 m²/g), though both had comparable average pore diameter and total pore volume. More studies are therefore needed where the same peel would be carbonized using both pyrolysis and HTC to determine which one produces better biosorbents.

Post-treatment of biosorbent

The main post-treatment of biosorbents is activation of the biosorbent to enhance its adsorption capacity through the improvement of its surface properties (Adeniyi *et al.* 2023). Although there are instances where peels have been treated with an activating agent

prior to carbonization (Liang *et al.* 2010, Mallampati *et al.* 2015, Abdić *et al.* 2018, Nhung *et al.* 2018, Singh *et al.* 2019, 2021, Jawad *et al.* 2021, El-Nemr *et al.* 2024b, Prabakaran *et al.* 2022, Wattanakornsiri *et al.* 2022), activation of the FVP-based biosorbents is usually done after carbonization as a post treatment (Heidarinejad *et al.* 2020). Activation could aim at removing organic matter blocking pores on the surface of the biosorbent or introducing elements and/or functional groups that could improve the adsorption capacity of the biosorbent. Like any other adsorbent, FVP-base biosorbents can be activated through either physical or chemical processes.

Physical Activation

Physical activation of biosorbents is done either in air, ozone, steam, or CO₂ under elevated temperatures of between 700 and 900°C (Ketabchi *et al.* 2023). Steam and CO₂ are the most used gases, and so physical activation is also referred to as gaseous activation (Sajjadi *et al.* 2019). These gases, some of which are also oxidizing agents, are able to penetrate the internal structure of the carbonized peels and gasify the carbon atoms. Sajjadi *et al.* (2019) highlight chemisorption, scavenging of surface oxide by carbon, carbon gasification, shift reaction, carbon gasification by water, carbon gasification by carbon dioxide, and carbon gasification by hydrogen as the main reactions responsible for physical activation of biosorbents using steam. The main purpose of gasification is to improve the surface area of the biosorbent through the creation of micropores and mesopores, which increase the surface area of the biosorbent and allow for rapid diffusion of adsorbates into the interior micropores of the biosorbent (Ahmad *et al.* 2023). A temperature of 800 to 900 °C for 30 to 180 minutes is recommended when using steam for gasification to activate biosorbents because these conditions improve the surface area, pore volume and oxygen containing functional groups in the biosorbent (Erkiaga *et al.* 2013).

Though air is more beneficial economically than the other oxidizing agents, it is not commonly used in physical activation of adsorbents because of its low reactivity (Sajjadi *et al.* 2019). Details of the effect of physical activation using the different gases have been reported in Sajjadi *et al.* (2019). Physical activation, however, has little effect on the biosorbent (Sakhiya *et al.* 2021). This was confirmed by Fu *et al.* (2016), who obtained decreased hydrogen and oxygen contents and average size of pores in biosorbents that were physically activated. The observed decreases were attributed to the minimal impact of physical activation on the biosorbents. Further to this, the high temperature requirement makes physical activation a high energy consuming process which increases the cost of producing the biosorbent. These challenges limit the use of physical activation of FVP-based biosorbents except in situations where the use of chemicals such as acid, alkalis and salts are to be avoided.

Chemical Activation

In chemical activation, chemicals are used at specific concentrations to react with the biosorbent for a certain period and at a given temperature to increase the number of active sites or functional groups on the biosorbent (Adeniyi *et al.* 2023) in an endeavor to improve its sorption capacity (Zhengfeng *et al.* 2023). Removal of inhibitory functional groups, chemical pyrolysis, halogenation, protonation, saponification, oxidation, and polymerization according to Pathak *et al.* (2015) and Ketabchi *et al.* (2023) are some of the reactions that may occur during chemical activation of biosorbents. Chemicals frequently used for chemical activation include acids (HCl, HNO₃, H₃PO₄, H₂SO₄), alkalis (KOH, NaOH), and salts (NaCl, MnCl₂, FeCl₃, ZnCl₂).

As stated by Kainth *et al.* (2024), the purpose of acid activation is mostly to remove metallic impurities contained in the biosorbent, though acids with high oxidation capacities could sometimes increase the surface area of the biosorbent by creating gaps between its carbon layers. Phosphoric acid (H_3PO_4) is among the frequently used acids to activate lignocellulosic materials (Yahya *et al.* 2015), especially those which have not been carbonized (Yakout and Sharaf El-Deen 2016). The main mechanisms of phosphate activation of lignocellulosic materials are depolymerization, dehydration, and the redistribution of biopolymers present in the biomass (Abdelnaeim *et al.* 2016). Through these processes, the acid groups on the surface of the biosorbent are increased, while mineral elements are eliminated with a resultant increase in the hydrophilicity of the biosorbent surface. This, according to Heidarinejad *et al.* (2020), facilitates access to aqueous media by the biosorbent. Some FVP-based biosorbents that have been successfully improved with H_3PO_4 activation are shown Table 4.

Table 4. Some Methods Used to Activate Peel-based Biochar for Pollutants Removal from Wastewater

Type of Peel	Fruit/ Vegetable	Activation Method and Chemicals Used for Activation	Removed Pollutant	Reference
Fruit	Banana	H_3PO_4	Pb (II)	Zhou <i>et al.</i> (2017)
		$MnCl_2 + KOH$,	Tetracycline	Zhang <i>et al.</i> (2023)
	Citrus	Citrus extract	Rhodamine B Methyl blue Methyl orange	Tran <i>et al.</i> (2022)
	Grapefruit	Grapefruit peel extract	Tetracycline	Yu <i>et al.</i> (2020)
	Litchi	Thermal	Congo red Malachite green	Wu <i>et al.</i> (2020)
	Lemon	H_3PO_4	Pb	Mohammadi <i>et al.</i> (2014)
	Mango	Thermal	Cd (II)	Zhang <i>et al.</i> (2019)
	Mandarin	1:1 ratio of NH_4Cl and $ZnCl_2$	Methyl Orange Fast green	Park <i>et al.</i> (2021)
	Orange	KOH	Cr (VI)	Zhengfeng <i>et al.</i> (2023)
	Pear	$FeCl_3 \cdot 6H_2O$	Methylene blue	Fakhar <i>et al.</i> (2022)
	Pomelo	KOH	Tetracycline	Cheng <i>et al.</i> (2020)
		H_3PO_4	Ciprofloxacin	Sun <i>et al.</i> (2016)
		KOH	Methyl Orange	Li <i>et al.</i> (2016)
Pome- granate	H_2SO_4	Methyl blue	Jawad <i>et al.</i> (2021)	
	KOH	Ramazol brilliant green	Ahmad <i>et al.</i> (2014)	
Watermelon	NH_4OH	Cu (II)	El-Nemr <i>et al.</i> (2024a)	
Vegetable	Avocado	Fe_3O_4 nano particles $FeCl_3 \cdot 6H_2O$	Methylene blue	Prabakaran <i>et al.</i> (2022)
	Onion	Fe_3O_4 nano particle	Cr (VI); methylene blue; Congo red	Kumar and Kumar (2022)
	Pea	H_2SO_4	Cr (VI)	El-Nemr <i>et al.</i> (2024b)
	Potatoes	TiO_2 Nanoparticles	Cr (VI)	Ashfaq <i>et al.</i> (2022)
		H_3PO_4	Co	Kyzas <i>et al.</i> (2016)
	Pumpkin	H_2SO_4	Methylene blue	Bal <i>et al.</i> (2021)
Watermelon	NH_4OH	Cu (II)	El-Nemr <i>et al.</i> (2024a)	

Another commonly used acid for chemical activation of biosorbents is sulphuric acid (H_2SO_4), which Jawad *et al.* (2021) have stated is used because it is a strong oxidizing agent that contains plenty of active sites. Acids are, however, highly corrosive, and so acid activated biosorbents need to be thoroughly washed before use.

Alkali activation, on the other hand, affects mainly the surface area of the biosorbents and so it improves its adsorption capacity more than acid activation according to Heidarinejad *et al.* (2020). Potassium hydroxide (KOH) has been extensively used to activate carbonized FVPs (Yakout and Sharaf El-Deen 2016) because it is cheap, produces biosorbents with high surface areas, and is environmentally friendly (Zou *et al.* 2016). The mechanisms involved in KOH activation include dehydration, reduction, oxidation, and hydration (Tounsadi *et al.* 2016). KOH activation is however less efficient than H_3PO_4 or ZnCl_2 , and it could also be more expensive because high temperatures of about $650\text{ }^\circ\text{C}$ are needed for activation (Heidarinejad *et al.* 2020). Another alkali used for activation is sodium hydroxide (NaOH). Gao *et al.* (2016) used NaOH and H_2SO_4 to activate *Ficus racemose* and found that the surface area of *Ficus* activated with NaOH ($136\text{ m}^2/\text{g}$) was higher than that of *Ficus* activated with H_2SO_4 ($41.8\text{ m}^2/\text{g}$). Considering the environmental effects of acids and alkalis, salts have also been used in chemical activation of biosorbents. According to Okoye *et al.* (2019), salts increase the surface area of biosorbents through the formation of holes in its carbonaceous structure. The most commonly used salt for chemical activation is ZnCl_2 (Heidarinejad *et al.* 2020). Though it has been widely used in the activation of lignocellulosic materials, not much has been reported on the activation of FVPs based biosorbents with ZnCl_2 . Adeniyi *et al.* (2023) mixed orange peels with ZnCl_2 at a ratio of 1:1 for 24 hours after which the mixture was boiled to evaporate the remaining water. The peels were then carbonized to produce a chemically modified biosorbent. Other methods of activation of biosorbents include the use of surfactants, esterification, magnetic materials, and grafting (Kainth *et al.* 2024). An extensive review on the activation of biosorbents using different methods has been presented by Heidarinejad *et al.* (2020).

The choice of chemical used in chemical activation is often controlled by the application for which the biosorbent is to be used, as well as the type of pollutants to be adsorbed. Alkalis are commonly used to activate biosorbents that are used for the removal of negatively charged elements, whereas acids are better activating agents when positively charged elements are targeted (Anto *et al.* 2021). Table 4 presents some of the chemicals used to activate FVP-based biosorbents and biochar. The data presented in Table 4 show that a variety of chemicals can be used for activation and that the activated biosorbent can be used for a variety of purposes. Activation could also occur on both raw and thermally treated FVPs. Chemical activation can be done prior to carbonization of the peels or after the peel has been converted to a biosorbent. Biosorbents produced in both cases present good surface properties, but the former method is the most frequently used because it helps to avoid tar formation and it removes volatile compounds and water (Adeniyi *et al.* 2023). Chemical activation of FVP-based biosorbents could also make use of a single chemical, or a mixture of chemicals (Table 4). Park *et al.* (2021) and Zhang *et al.* (2023) in their studies showed that chemical activation with two chemicals could also improve the surface properties of biosorbents. However, excess use of chemicals to activate biosorbents can be detrimental, as traces of the chemicals could remain on the biosorbent even after a series of washings. Such biosorbents may be unsuitable for use wherever toxicity is of concern such as in food processing, medicine, and pharmaceutical industries.

The toxicity and environmental impacts of some of the chemicals used for activating biosorbents have triggered research into the use of extracts from peels and other

bio-activators as activating agents for biosorbents. Efeovbokhan *et al.* (2019) studied the effectiveness of activating biosorbents made of coconut shells and peels from unripe plantains first with lemon juice (acidic), followed by the extract of unripe plantain peels (alkaline). Their results revealed that bio-activators provided better characteristics to the biosorbent than when using KOH. However, in the case of the removal of tetracycline, activation by KOH showed better removal efficiency than that of peel extract. In terms of cost, the use of peel extract is advantageous, and no secondary waste is produced. Acid, alkali, and salt activation yield better biosorbents, but they should be used with moderation to minimize secondary toxic waste and corrosion of the equipment throughout the process. More studies are needed to understand which activation method is better suited for which peel base biosorbent and the conditions under which the activation should be carried out.

Other methods of activating biosorbents include microwave activation, where the polar atoms or molecules of the peel absorb energy and collide with neighboring molecules as they vibrate, generating thermal energy (Sajjadi *et al.* 2019). This energy then promotes the production of volatiles and the development of a porous structure inside the biomass while releasing gases such as H₂, CO, CO₂, CH₄, C₂H₄, and C₂H₆. Various chemical reagents are used in microwave activation to selectively treat and modify the functional groups present in the biosorbent, and so microwave activation can be regarded as a form of chemical activation. Plasma and ultrasound activation are also methods that have been exploited in the activation of biosorbents. However, these technologies may be expensive and are likely to increase the cost of producing biosorbents from FVPs, compromising their use as low-cost adsorbents. Generally, chemical activation is more costly than physical activation of biosorbents (Sakhiya *et al.* 2021). Ighalo *et al.* (2022) have also indicated that using both chemical and physical activation of biosorbent is more expensive than using physical or chemical activation alone. The need for activation of peel-base biosorbents adds to the overall cost of the adsorbent, especially if synthetic chemicals are to be used for activation. This cost could be offset by using natural extracts as chemical activators. Biosorbent activation with natural extracts needs further studies to identify ways of optimizing the process such that they could be comparable with acid, alkali, and salt activation.

SELECTED PHYSICO-CHEMICAL AND THERMAL PROPERTIES OF FVP-BASED BIOSORBENTS

The physical and chemical characteristics of biosorbents influence the application for which they can be used, their efficiency, and the type of pollutants they can absorb (Pathirana *et al.* 2019). Various researchers have shown that biosorbents have better surface properties than their corresponding raw materials, as reflected by the chemical properties of FVPs in Tables 3 compared with biosorbents made from these peels in Table 5. The functional groups are more numerous in the biosorbents relative to the FVPs, and this is also true for their elemental content, surface area, and porosity (Table 5). Great variations are observed in the specific surface area of the biosorbents (Table 5), depending on the process used for their carbonization and the chemical used for activation. Most FVP-based biosorbents contain lower amounts of ash (below 20%), with some like potato peel-based biosorbent having slightly higher ash content (26%). FVP-based biosorbents contain relatively high amounts of C and O, with the highest C (78%) and O (50%) found in mango and orange peels respectively (Table 5).

Table 5. Characteristics of Selected Fruit and Vegetable Peel-based Biosorbents

Type of Fruit or Vegetable	Type of Pyrolytic Method used for Biochar Production	Ultimate Analysis							Proximate Analysis					Reference
		C	N (%)	O (%)	pH	Functional Group	BET SSA (m ² /g)	Total Pore Volume (cm ³ /g)	FC (%)	Mois-ture (%)	Ash (%)	VM (%)	HHV (MJ/kg)	
Apple	Microwave heating	72.52	0.97	23.75	-	Aldehydes, alcohol, carbonyl, alkene, carboxylic	1552	2.59	7.4	12.27	7.43	72.89	-	(Hoseinzadeh <i>et al.</i> 2013)
Banana	Slow pyrolysis	54.0-58.0	1.0-1.3	34.7-42.0			8.0-51.0	0.005-0.030	46.6-67.6	3.4-6.4	3.0-10.5	15.5-47.0	-	(Lam <i>et al.</i> 2018; Foroutan <i>et al.</i> 2022)
Potato	Slow pyrolysis	55.1-63.8	1.47-2.49	6.24-26.1	9.72-12.6	Alcohol, phenol, ether, alkane, alkene	3-1912	0.002-117	18-60.6	4.15-5.2	12.1-26.35	13-29.87	25.4	(Sun <i>et al.</i> 2017; Yang <i>et al.</i> 2018; Osman <i>et al.</i> 2019; Gholami and Rahimi 2021; Khalafallah <i>et al.</i> 2021; Singh <i>et al.</i> 2022; Vilakazi <i>et al.</i> 2023)
Orange	Slow Pyrolysis	50.6-77.8	1.76-6.20	14.4-41	9.97-10.1	Alcohol, ester, alkane, phenol, carbonyl,	22.8-132.2	0.0098-0.068	51.9-81.5	6.2-8.6	0.45-15.03	12.7-45.8	-	(Chen and Chen 2009) (Sial <i>et al.</i> 2019; Kumar and Kumar 2022)
	Fast Pyrolysis	47.8	1.19	43.53	-	alcohols, phenols, or carboxyl	2.7	0.007	25.2	4.18	2.15	72.65	18.59	(da Silva <i>et al.</i> 2022)

Lemon		51.41-72.29	1.5-2.87	21.35 - 41.68	-	Alcohol, carbonyls, amide,	5.48-1085.0	0.016-0.19	1.34-19.93	0.34-1.97	5.84-9.49	58.6-75.8	19.9-24.42	(Park <i>et al.</i> 2021) (Yılmaz and Tugrul 2021); (Abidi <i>et al.</i> 2023)
Mango	Slow pyrolysis	51.84-78.6	0.80 - 1.34	9.93-43.63	6.5-6.87	Alcohol. Phenol, alkane carbonyl	2.09-6.61	0.009-7.48	67.35	4.04-13.29	2.16-9.04	14.58	-	(Jawad <i>et al.</i> 2021; Zhang <i>et al.</i> 2021) (Rind <i>et al.</i> 2022)
Durian	Slow pyrolysis	64.49-68.68	0.93-1.04	15.14-18.37	9.9-10.33	Carbonyl, hydroxide, Carboxyl	0.7496 -	-	49.14-50.17	8.9 - 9.24	9.38-10.41	30.49-32.24	24.49-24.98	(Prakongkep <i>et al.</i> 2014; Manmeen <i>et al.</i> 2023)
Pineapple	Slow pyrolysis	72.95-73.90	0.79 - 1.23	9.88-12.5	7.7-9.74	Hydroxyl, Alkyl, Alkene, Aromatic	0.815 - 11.112	0.0015 - 0.0017	42.49-71.03	1.76 - 4.14	6.58 - 13.23	15.47-45.79	21.89-23.50	(Fu <i>et al.</i> 2016; Shakya and Agarwal 2019; Hu <i>et al.</i> 2020);
Pomegranate	Slow pyrolysis	45.3-68.89	0.78	18.29-49.9		Hydroxyl, Carbonyl, phenyl, alkane	1.01-526.6	0.00011 -247	-	3.56	6.34	42.78	23.5	(Siddiqui <i>et al.</i> 2019; Jawad <i>et al.</i> 2021; Oymak and Şafak 2022)
Pumpkin	No thermal treatment	68.9	3.5		5	carboxylic acid, aliphatic ether, alcohol	689.9	0.6	68.3	14	6.4	25.4	-	(Özer and İmamoğlu 2024)

The elemental concentrations and elemental ratios in the biosorbents indicate high stability, good decomposition of lignocellulosic matter, and good polymerization and aromaticity of the peels during carbonization.

Volatile matter content is high (72.9%) in biosorbents obtained from apple peels compared to the other peels (Table 5). This could probably be attributed to the difference in carbonization method used as the apple peels were treated using microwave, whereas the rest were carbonized using slow pyrolysis (Table 5).

The total pore volume of most of the biosorbents increased with an increase in pyrolysis temperature. Most of the peel-based biosorbents are alkaline, as their pH values were above 7 (Table 5). The surface properties of the treated FVP-based biomasses are much better than their natural forms and are likely to be more efficient as adsorbents.

APPLICATION AND EFFICIENCY OF FVP-BASED BIOSORBENTS IN WASTEWATER TREATMENT

Studies have shown increasing potential of biosorbents prepared from FVPs to remove various pollutants in effluents from different industries. The mechanism of adsorption of pollutants by biosorbents varies depending on the raw material of the biosorbent and the pollutant in question (Kainth *et al.* 2024). Processes associated with biosorbents removal of pollutants from wastewater include ion exchange, chemical complexation, and the hydrophobic effect, among others (Li *et al.* 2010; Hubbe *et al.* 2011; Hubbe *et al.* 2014; Nartey and Zhao 2014). Ion exchange is the most widely reported mechanism of heavy metal removal by biosorbents. In ion exchange, a replacement of an ion present on the surface of the adsorbent by the pollutant in solution occurs (Hubbe *et al.* 2011). Wattanakornsiri *et al.* (2022) proposed a metal adsorption mechanism where ion exchange occurs between the carboxyl, phenolic, and hydroxyl functional groups found in the biosorbent and the metals. Khare and Goyal (2013), indicated that the main mechanisms of heavy metal removal using biosorbents are cation exchange, precipitation, electrostatic interaction, chemical reduction, and complexation.

When pollutant compounds contain hydrophobic groups, these often play a prominent role in their adsorption onto carbon-based adsorbents. Though these groups can self-associate due to the ever-present van der Waals forces, such interactions are weaker in comparison to hydrogen bonding. The term “hydrophobic effect” describes a tendency for nonpolar groups, such as alkyl or aromatic, to either self-associate or to precipitate onto hydrophobic surfaces, thus allowing a maximum number of hydrogen bonds to form in the adjacent bulk water phase. Thus, hydrophobic interactions were also listed as the mechanism involved in the adsorption of petrochemical compounds by biosorbents (Kong *et al.* 2012; Zheng 2013; Hubbe *et al.* 2014). Jalilian *et al.* (2024) attributed the mechanism of organic pollutant binding by biosorbents to either pore filling, electrostatic interactions, hydrogen bonding, or π - π interactions. Qiu *et al.* (2022) stated that in most cases, more than one of these mechanisms are involved. Diffusion within the biosorbent has been highlighted as the main mechanism that limits the rates of uptake of pollutants from water (Li *et al.* 2010; Hubbe *et al.* 2012). Experiments can determine whether the rate-limiting step in removal of a pollutant from the aqueous phase is bulk diffusion or intra-particle diffusion. Stirring can be an effective way to overcome issues related to diffusion in the bulk aqueous phase.

Table 6. Percentage Removal of Pollutants from Various Solutions by Peel-based Biosorbents

Pollutant type	Pollutant name	Vegetable or fruit peel	Removal efficiency (%)	Reference
Organic	Tetracycline	Pomelo	80 to 100	Cheng <i>et al.</i> (2020)
		Grapefruit	87.0	Yu <i>et al.</i> (2020)
	Rhodamine B	Tapioca	77 to 96	Vigneshwaran <i>et al.</i> (2021a)
		Citrus	69.3	Tran <i>et al.</i> (2022)
		Pomegranate	90.0	Mankomal and Kaur (2022)
		Banana	81.11	Singh <i>et al.</i> (2018)
	Methyl orange	Citrus	51.5	Tran <i>et al.</i> (2022)
	Congo red	Onion	98.9	Kumar and Kumar (2022)
		Litchi	80.0	Wu <i>et al.</i> (2020)
		Banana	75.3	Mondal and Kar (2018)
	Malachite green	Litchi	99.1	Wu <i>et al.</i> (2020)
		Tapioca	67.1 to 88.7	Vigneshwaran <i>et al.</i> (2021a)
	Methyl blue	Pear	99.8	Fakhar <i>et al.</i> (2022)
		Citrus extract	95.5	Tran <i>et al.</i> (2022)
		Pomegranate	93.9	Jawad <i>et al.</i> (2021)
		Onion	95	Kumar and Kumar (2022)
		Pumpkin	94.0	Bal <i>et al.</i> (2021)
		Avocado	96.4	Prabakaran <i>et al.</i> (2022)
		Pomegranate	94.0	Mankomal and Kaur (2022)
Cucumber		81.4	Shakoor and Nasar (2017)	
Crystal violet	Orange	86.7	Ahmed & Majewska-Nowak (2020)	
Organophosphate	Potato	72.0	Singh <i>et al.</i> (2022)	
Phenol	Pomegranate	91.0	Mankomal and Kaur (2022)	
Inorganic	Ag	Bottle gourd	95.0	Ahmed <i>et al.</i> (2018)
	As	Pomelo	80 to 100	Nguyen <i>et al.</i> (2022)
	Cr	Pea	90.7	El-Nemr <i>et al.</i> (2024b)
		Potatoes	83.8 to 86.5	Ashfaq <i>et al.</i> (2022)
		Onion	94.1	Kumar and Kumar (2022)
	Cd	Rambutan	97.1	Wattanakornsiri <i>et al.</i> (2022)
		Dragon fruit	96.7	
		Passion fruit	93.4	
		Banana	90.1	
	Cu	Watermelon	72 to 100	El-Nemr <i>et al.</i> (2024a)
		Orange	96.0	Sireesha <i>et al.</i> (2022)
		Banana	45-80	Sun <i>et al.</i> (2023)
		Bottle gourd	99.0	Ahmed <i>et al.</i> (2018)
	Ni	Orange	98.0	Sireesha <i>et al.</i> (2022)
		Potato/carrot	79.3	Gill <i>et al.</i> (2013)
	Pb	Banana	90.0	Zhou <i>et al.</i> (2017)
		Cantaloupe	92.2	El Refaey and Mohammad (2019)
		Onion	88.5 to 99.9	Olasehinde <i>et al.</i> (2018)
		Dragon fruit	76.6	Wattanakornsiri <i>et al.</i> (2022)
		Rambutan	97.8	
Passion fruit		94.5		
Ammonium	Orange	98	Hu <i>et al.</i> (2020)	
	Pineapple	75	Hu <i>et al.</i> (2020)	

The removal efficiency of organic pollutants by FVP-based biosorbent is up to 99.9% for some biosorbents, and the level of removal varies with the operating conditions,

type of biosorbent, modification method applied on the biosorbent, and physicochemical properties of the wastewater treated (Singh *et al.* 2022; and Zeghioud *et al.* 2022). Mankomal and Kaur (2022), Yu *et al.* (2020), and Wu *et al.* (2020) have all reported on the efficiency of using various FVP-based biosorbents to remove organic pollutants from various waters, as shown in Table 6. More studies on the efficiency of fruit peels in the removal of organic and inorganic pollutants can be found in Harshala and Wagh (2022), and Sánchez-Ponce *et al.* (2022).

Lee *et al.* (2019) stated that the removal efficiency of organic pollutant using biosorbent increases when the FVPs are pyrolyzed at moderately high temperatures (500 to 700 °C), while both low (300 °C), and high temperature (above 700 °C) pyrolysis produce biosorbents with less efficiency. In some instances, the peel-based biosorbent showed potential in the simultaneous removal of organic and inorganic pollutants. For instance, banana peel-based biosorbents were used by Hu *et al.* (2021) to remove both Pb and tetracycline from contaminated water. Nathan *et al.* (2022) also showed simultaneous removal of Cd, Cu, Hg, Ni, Pb, Cr, and As using treated peels of kiwi fruit with removal efficiencies of 92%, 84%, 80%, 75%, 67%, 34%, and 17%, respectively. This is a particularly good attribute of peel-based biosorbent as a low-cost absorbent as it could further reduce the cost of pollutant removal through adsorption.

The efficiency of biosorbents in the removal of inorganic pollutants from wastewater also varies. Sireesha *et al.* (2022) conducted a study on orange peel and sweet lemon peel-based biosorbents to determine which of them performs better in the removal of heavy metals from wastewater and found that orange peel-based biosorbent was the better performing biosorbent with a removal efficiency of 96% and 98% for copper and nickel, respectively. Hu *et al.* (2020), Nguyen *et al.* (2022), and Sun *et al.* (2023) have also reported on the efficiency of pineapple, orange, pomelo, and banana peel based biosorbents in removing various metals from waters, as shown in Table 6. Hu *et al.* (2020) in their study on the removal of ammonium concluded that biosorbents produced at lower pyrolysis temperature (300 °C) could be better at removing inorganic pollutants from water than those produced at higher temperatures (400, 500, and 600 °C).

FVP-based biosorbents also show some efficiency in removing anionic pollutants from wastewater. In a study conducted by Chen *et al.* (2022), an improvement in the removal of phosphate by orange peel-based biosorbent activated by Ca/Zn composite was observed. Nayak *et al.* (2021) used modified jack fruit peel biosorbent to remove and recover both phosphate and nitrate from municipal wastewater. Maximum adsorption capacities of 7.94 and 5.26 mg/g for phosphate and nitrate respectively were obtained. Reddy *et al.* (2015) used banana peel to remove nitrates from water and obtained a removal efficiency of 80%. These studies all highlight the potential of FVP peel-based biosorbents in the removal of a variety of pollutants from diverse types of wastewater.

POTENTIAL OF FVPS AS PRECURSOR FOR BIOSORBENT PRODUCTION

The chemical and physical properties of FVPs indicate that they have enormous potential as raw materials for biosorbent production. They contain important chemical compounds, functional groups, and elements that could make any FVP-based biosorbent attractive and efficient in the adsorption of both organic and inorganic pollutants from wastewaters. Even when the characteristics of the FVPs do not meet certain requirements, there are possibilities of modifying the growth conditions of the fruits and vegetables to

obtain desirable characteristics for their peels. The amount of peels rejected during fruit and vegetable consumption and processing guarantees supply of peels as raw material for biosorbent production, and they could be acquired at no cost. In addition, the transformation of FVPs to biosorbents is often easy, and the reaction is quick. To make the process even more affordable, the peel-based biosorbents can be activated with peel extracts, which is also efficient in improving the surface properties of the biosorbents with no environmental risk. Their efficiency in the removal of organic, inorganic, and anionic pollutants is comparable with the efficiency of commercial activated carbon and other adsorbents which are usually expensive. These factors make the use of FVPs as raw materials for low-cost adsorbent attractive. More efforts need to be invested in optimizing pyrolysis conditions of peel biomass so that the surface properties of FVP-based biosorbents would improve. Such improvement could include improvement of surface area, specificity, and modification of the functional groups to increase absorption capacity. Further studies could also focus on identifying possible combinations of peels that could result in biochar and biosorbents with high efficiency.

CONCLUDING STATEMENTS

High costs associated with adsorption as a wastewater treatment process can be offset by using low-cost adsorbents made from fruit and vegetable peels. They have proved to be effective as adsorbents, especially when suitably treated. Hydrothermal treatment, due to its moderate energy demand and cost, has shown promise as a means to prepare carbon-rich material from FVPs. Subsequent or concurrent activation treatments can create pores and increase the surface areas, thus improving the adsorption capacities of these biosorbents. The use of FVPs as raw materials for biosorbent production brings together both environmental relief through the reduction of the amount of waste disposed, and good waste management practice, as it promotes recycling. Waste valorization and recycling are highly recommended to mitigate the amount of pollutants to be discharged into the environment. Using FVPs as raw materials for biosorbents could significantly reduce the energy requirement of producing adsorbents that could be used in the treatment of wastewater from a variety of sources and consequently the overall costs of the method. Most of the studies on peels as raw materials for biosorbents have focused on using single peels or peels and other high carbon materials such as sewage sludge. Investigations on how peels from different vegetables and fruits could be combined to improve their performance as low-cost adsorbents are needed. Similarly, studies are needed to optimize the performance of natural plant extracts as possible chemicals to be used in biosorbent activation to reduce the environmental risk and cost associated with chemical activation of peels. All these efforts are likely to further enhance the use of FVPs as biosorbents or raw materials for biosorbent production.

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