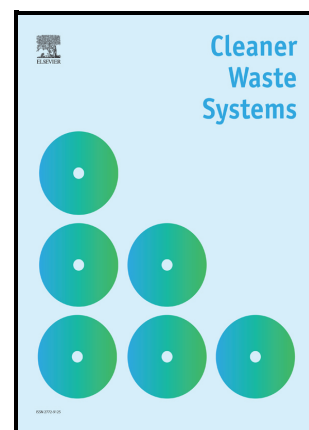


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Sustainable utilization of citrus peel waste: Biochar production, modification, and applications

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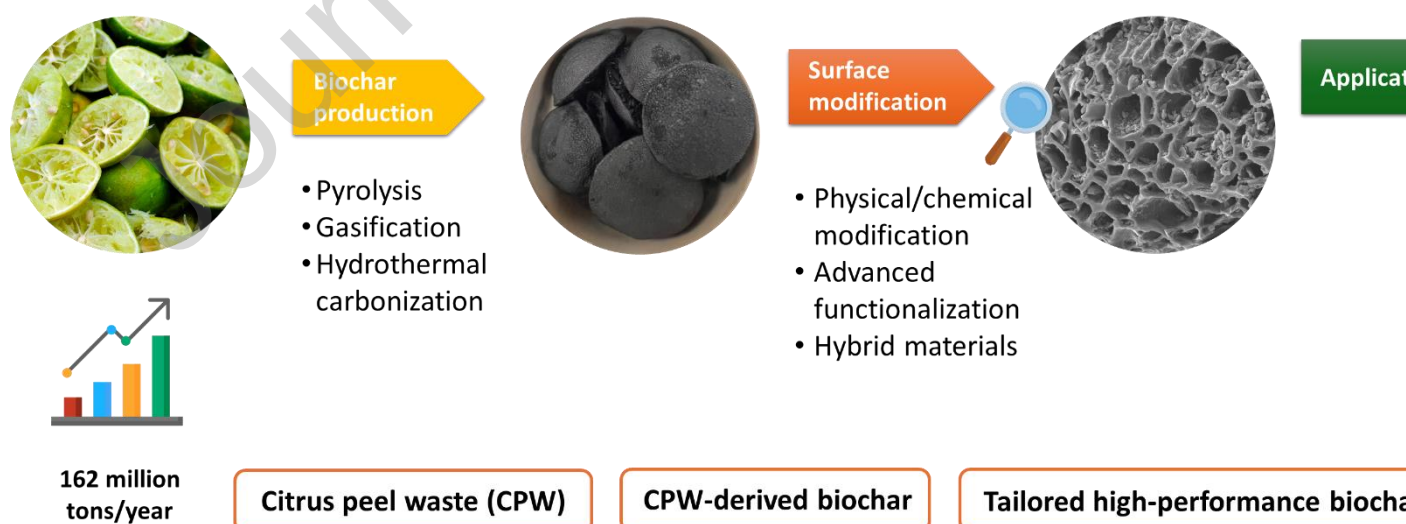
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Abstract

Citrus peel waste (CPW) is generated in substantial quantities worldwide and poses an environmental burden through improper disposal; however, its high lignocellulose content makes it a promising feedstock for producing value-added biochar. This review aims to critically synthesize recent advances in CPW-derived biochar production, modification, and applications within a circular bioeconomic context. Key findings show that pyrolysis conditions, feedstock variability, and activation strategies strongly influence biochar yield, pore development, and functional chemistry. Physical, chemical, and hybrid surface modification techniques substantially increase the adsorption selectivity and efficiency. CPW-derived biochars effectively remove heavy metals, organic pollutants, and nutrient contaminants, and offer additional benefits in terms of soil improvement, carbon sequestration, and emerging biomedical applications. Despite these advantages, challenges remain regarding feedstock heterogeneity, process scalability, regeneration performance, and environmental safety. Overall, the valorization of CPW into biochar represents a sustainable pathway for waste reduction and environmental remediation, with future opportunities in advanced material engineering and alignment with global sustainability goals.

Graphical abstract



Keywords: Biochar production, Citrus peel waste valorization, Environmental remediation, Pollutant adsorption, Surface modification

1. Introduction

Citrus fruits including oranges (*Citrus sinensis*), lemons (*Citrus limon*), tangerines (*Citrus reticulata*), and grapefruits (*Citrus paradisi*), are among the most widely cultivated fruit crops worldwide. According to statistics from the Food and Agriculture Organization of the United Nations, citrus production has consistently exceeded 150 million tons annually. Moreover, global citrus production has steadily increased over the past two decades, driven predominantly by Asia, followed by South America and Africa (Fig. 1(a)). The total citrus yield reached nearly 162 million tons in 2021, reflecting both the growing consumer demand and the expansion of cultivation areas worldwide (United Nations Statistics Division, 2025). Particularly, nearly half of this mass ends up as citrus peel waste (CPW) (Zema et al., 2018), that leads to enormous quantity of biowaste (Fig. 1(b)), being often discarded or underutilized. The substantial disposal challenges are due to its high moisture content, rapid biodegradability, and potential to generate methane and leachate if unmanaged (Sharma et al., 2022).

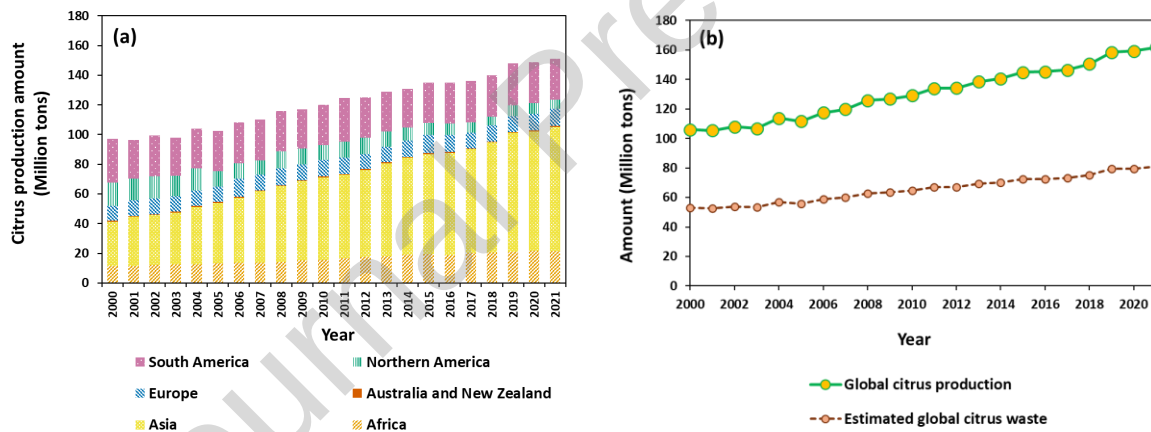


Fig. 1. Global citrus production and citrus peel waste estimation from 2000 to 2021. (a) Citrus production amount by continent, highlighting the dominant contribution from Asia, followed by South America and Africa. (b) Global citrus production and the projected citrus peel waste generation, estimated as ~50% of the total production (United Nations Statistics Division, 2025).

As a biowaste, CPW has the potential as a feedstock in thermoconversion processes, generating not only gas and or liquid products, but also solid fractions (e.g. biochar) that can be further functionalized as added-value materials. In fact, biochar, a carbon-rich porous material produced via pyrolysis under oxygen-limited conditions, has received increasing

attention for its role in environmental remediation, soil management, and circular economy practices (Lehmann and Joseph, 2015). Existing biochar reviews have generally taken one of three directions: (i) focusing on biochar from mixed agricultural wastes, (ii) discussing broad biochar applications such as wastewater treatment or soil enhancement, or (iii) addressing specific modification techniques without linking them to particular feedstocks. The transformation of CPW into biochar not only addresses the environmental burden of fruit-processing residues but also yields high-value carbonaceous materials with tailored functionalities. Compared with biochar from typical lignocellulosic residues such as rice husks, corncobs, sawdust, and mixed fruit wastes, biochar derived from CPW has distinctive features (Zhang, A. et al., 2024; Tan et al., 2015; Nanda et al., 2016; Selvarajoo et al., 2022). Owing to its high volatile content, low ash fraction, and abundance of oxygenated functional groups, CPW tends to produce biochar with high reactivity, superior surface functionalization potential, and favorable adsorption properties (Selvarajoo et al., 2022). In addition, the presence of bioactive compounds uniquely influences thermal degradation pathways, pore evolution, and suitability for advanced surface treatments and hybrid material formation. CPW-derived biochar has high porosity, significant surface functionalization potential, and the ability to remove pollutants from wastewater (Mishra et al., 2023). Several studies have explored the production of biochar from CPW and its subsequent applications. Key research areas include optimizing pyrolysis conditions, surface modifications to increase the adsorption capacity, and evaluating the performance of biochar in removing pollutants such as heavy metals, organics, and inorganic contaminants (Chen et al., 2022). Recent advancements in biochar functionalization techniques, such as impregnation with metal oxides or acid treatments, have further improved the adsorption efficiency of citrus-derived biochar (Jiang et al., 2022).

CPW-derived biochar behaves differently from other biomass-derived biochars because of its unique chemical composition, diverse peel morphologies, and varying physicochemical characteristics across citrus species. These nuances have not been systematically reviewed or critically compared. Therefore, this review fills that gap by providing (i) a critical synthesis of how CPW-specific properties influence pyrolysis behavior, carbon yield, pore development, and functional group evolution; (ii) an integrated assessment of physical, chemical, and hybrid surface modification techniques tailored for CPW biochar; (iii) a comparative evaluation of adsorption and functional performance relative to conventional biochars; and (iv) a circular bioeconomic perspective, highlighting valorization pathways, environmental benefits, and alignment with Sustainable Development Goals (SDGs)

(Shoudho et al., 2024). The aim of this review is to critically examine the potential of CPW-derived biochar in three interconnected areas.

(1) Production and physicochemical properties - how type of feedstock and thermoconversion operational parameters influence CPW biochar yield, characteristics, and performance.

(2) Surface modification strategies - including physical activation, chemical treatments, doped/functionalized systems, and hybrid approaches to the physicochemical properties, adsorption, and catalytic performance of CPW biochar.

(3) Environmental and value-added applications - focusing on heavy metals, organics, and nutrient removal; soil amendment and carbon sequestration; and emerging uses in biomedical materials.

Additionally, the review identifies key challenges, including scalability, feedstock heterogeneity, regeneration, and potential environmental risks, and outlines future directions for advancing CPW valorization within sustainable waste management frameworks.

2. Review methods

This review adopted a scoping/narrative approach to summarize the current state of knowledge regarding the utilization of CPW for biochar production, surface modification, and diverse applications. Rather than following a rigid systematic review protocol, the methodology was designed to capture a broad range of relevant studies across different research domains.

2.1. Selection criteria

Studies were included if they were 1) published in English-language, peer-reviewed journals up to 2025; 2) focused on citrus-derived feedstock (lemons, oranges, tangerines, grapefruits) converted into biochar; and 3) reported at least one of the following aspects: (i) production methods and pyrolysis parameters; (ii) surface modification approaches; or (iii) applications in pollutant adsorption, soil management, or biomedical/environmental contexts. Studies that were purely theoretical, opinion pieces, nonpeer-reviewed reports, or gray literature were excluded.

2.2. Screening and classification

Articles identified from the database searches were first screened by title and abstract to confirm their relevance. Eligible studies were then reviewed in full and categorized under the main themes of this review:

- Biochar preparation techniques and physicochemical properties,
- Surface modification strategies,
- Environmental and agricultural applications,
- Challenges and future perspectives.

2.3. Data extraction and synthesis

The review is qualitative in nature. The extracted information included the feedstock type, pyrolysis conditions, modification methods, and reported applications. Instead of meta-analysis, emphasis was placed on identifying patterns, recurring techniques, comparative advantages, and knowledge gaps to guide future research directions.

2.4. Limitations

This review did not employ strict systematic review metrics or statistical meta-analyses. As a narrative review, its aim is to provide a broad and integrative perspective across disciplines. Nonetheless, care was taken to consult multiple databases and apply clear inclusion and exclusion criteria to ensure coverage of relevant and high-quality studies.

3. Results

An integrated synthesis of the production, modification, and application of CPW-derived biochar is provided in this section. It begins by outlining the thermochemical conversion pathways used to generate biochar from citrus residues, followed by an examination of how operational parameters influence physicochemical properties. The subsequent subsections describe surface modification strategies and their implications for targeted environmental uses. A conceptual overview summarizing the production steps, modification strategies, and downstream applications of CPW-derived biochar is presented in Fig. 2, offering a visual guide to the overall framework discussed in this section.

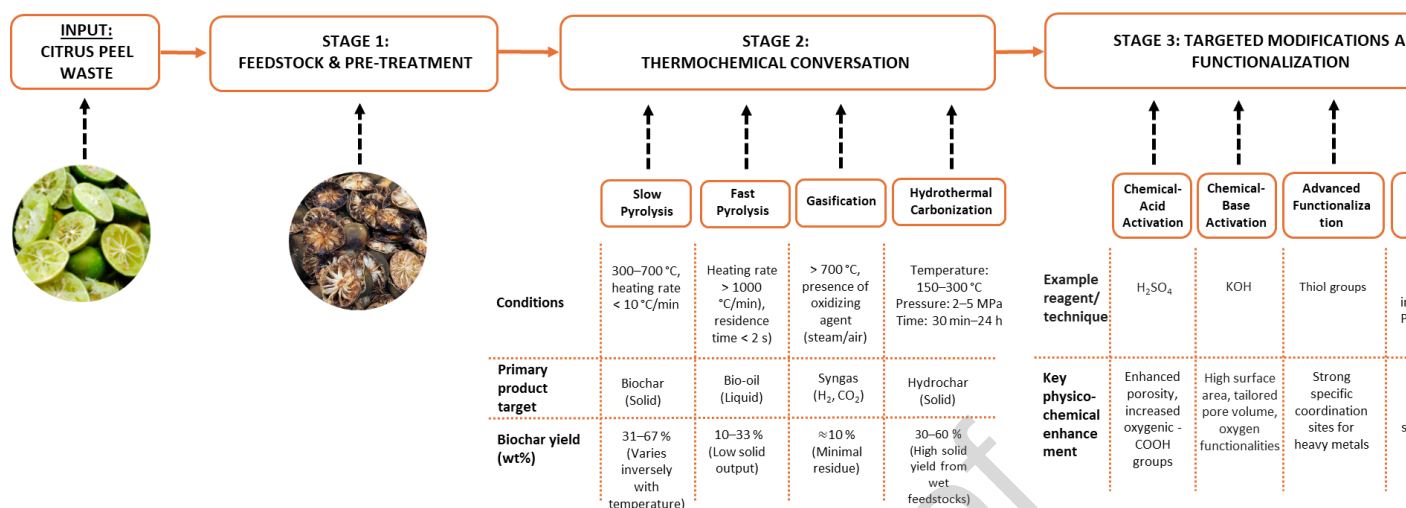


Fig. 2. Conceptual flow diagram summarizing citrus peel waste conversion into biochar, including feedstock preparation, thermochemical processing, modification strategies, and major environmental applications.

3.1. Preparation of citrus peel waste-derived biochar

CPW can be converted into biochar through several thermochemical routes. As with other lignocellulosic biomasses, the main options are slow pyrolysis, fast pyrolysis, and gasification, which differ in operating temperature, heating rate, residence time, and oxidizing atmosphere (Ronsse et al., 2013). However, CPW has a distinctive composition that is rich in pectin, cellulose, hemicellulose, and essential oils and generally contains less lignin than woody feedstocks do (Kim et al., 2015; Selvarajoo et al., 2022). These traits cause CPW to devolatilize at lower temperatures and within a narrower thermal window than many other conventional agricultural residues do. As a result, both the carbon yield and the development of pore structure differ from those of typical lignocellulosic biochars. Understanding these distinctions is crucial for selecting appropriate conversion conditions and for positioning CPW-derived biochar relative to other biochars used in environmental applications. In addition to dry pyrolysis routes, CPW can also be converted via hydrothermal carbonization (HTC), yielding a solid product commonly termed hydrochar. In this review, hydrochar is discussed alongside pyrolysis-derived biochar because of its similar role as a porous carbonaceous adsorbent, while its distinct oxygen content and aromaticity are explicitly highlighted where relevant.

3.1.1. Preparation techniques

As mentioned above, biochar can be obtained through different thermochemical conversion techniques, most prominently slow pyrolysis, fast pyrolysis, gasification, and HTC. These processes are defined by distinct operating parameters, which, together with the feedstock type, determine the yield, carbon content, surface area, pore structure, and functional groups of the resulting biochar (Ronsse et al., 2013; Manyà, 2012). CPW has been investigated under all four routes, and comparisons with other lignocellulosic feedstocks highlight both the advantages and limitations of this waste stream.

(1) Slow pyrolysis

Slow pyrolysis, typically conducted at 300–700 °C with heating rates below 10 °C/min and vapor residence times of minutes to hours, is optimized for relatively high biochar yields. Under these conditions, biomass is gradually carbonized, favoring solid output over liquid and gaseous fractions. As observed for many agricultural residues, the biochar yield decreases with increasing temperature, whereas the fixed carbon content, aromaticity, and stability generally increase (Manyà, 2012; Manyà et al., 2018). For CPW, Selvarajoo et al. (2022) reported a reduction in biochar yield from 53.62 wt% to 22.01 wt% as the pyrolysis temperature increased from 300 to 700 °C for mixed citrus peels (mainly lemon and orange). The decline was attributed to volatilization and secondary decomposition of lignocellulosic components by increasing pyrolysis temperatures (Selvarajoo et al., 2022; Mohd Hasan et al., 2019). The sensitivity of biochar yield to pyrolysis temperature is somewhat stronger than that of high-lignin woody feedstocks, where char yields often remain relatively high even at 500–600 °C owing to greater formation of thermally stable aromatic structures. Importantly, Aon et al. (2015) compared biochar derived from citrus peel with that derived from green waste under identical low-temperature conditions (300 °C). CPW yielded approximately 15% more char than did green waste, underscoring its suitability as a precursor for biochar production in low-temperature, energy-efficient processes. This suggests that, while CPW may not outperform woody biomass at very high temperatures in terms of carbon yield, it offers a favorable balance of yield and reactivity in the low to moderate temperature range, an aspect that has been underrepresented in previous broad biochar reviews. Overall, slow pyrolysis of CPW provides char yields that are comparable to or higher than those of many nonwoody agricultural residues at similar temperatures, while producing a more reactive, less graphitized carbon matrix. This reactivity is advantageous for adsorption and catalytic applications but may limit long-term persistence in soil carbon sequestration, highlighting a trade-off that remains insufficiently quantified.

(2) Fast pyrolysis

Fast pyrolysis is carried out at much higher heating rates (often $> 1000\text{ }^{\circ}\text{C}/\text{min}$) with very short vapor residence times (typically $< 2\text{ s}$), and is generally optimized for the production of bio-oil rather than biochar (Manyà, 2012; Alvarez et al., 2018; Muhammad et al., 2025). For most lignocellulosic feedstocks, the solid fraction is limited to approximately 10–15% under such conditions. For CPW, the high pectin content and relatively low lignin proportion led to a distinct devolatilization behavior. Kim et al. (2015) reported two main decomposition stages: pectin degradation at $150\text{--}250\text{ }^{\circ}\text{C}$ and cellulose/hemicellulose decomposition at $200\text{--}400\text{ }^{\circ}\text{C}$, overlapping with lignin degradation at relatively high temperatures. Consequently, fast pyrolysis of citrus peels tends to yield bio-oils rich in oxygenated volatiles (e.g., methanol and light oxygenates) and relatively poor in aromatic hydrocarbons compared with those of woody feedstocks. Selvarajoo et al. (2022) further emphasized that rapid heating after attaining the target temperature favors the liquid fraction while suppressing char formation. From a biochar perspective, this implies that CPW behaves similarly to other low-lignin residues: it is better suited to liquid bioenergy or biochemical production than to high-yield char production under fast-pyrolysis conditions. This distinction is important when positioning CPW within integrated biorefineries, yet direct comparisons of CPW with other fast-pyrolyzed feedstocks in terms of char quality remain scarce, highlighting a knowledge gap.

(3) Gasification

Gasification, unlike pyrolysis, is performed with a controlled amount of oxidizing agent (air, oxygen, or steam) at relatively high temperatures ($> 700\text{ }^{\circ}\text{C}$), aiming to maximize syngas production (mainly H_2 , CO , CH_4 , and CO_2) while generating relatively small amounts of biochar and tar (Prestipino et al., 2017). The process involves stepwise decomposition of hemicellulose, cellulose, and lignin into gaseous species with limited solid residue. He et al. (2022) compared citrus peel-derived biochar with pine sawdust-derived biochar under gasification conditions and reported that the carbon conversion efficiency of CPW biochar reached $\sim 97\%$, whereas only 77% was achieved for pine sawdust. The higher reactivity was attributed to the lower degree of graphitization in the CPW-derived biochar, which facilitates gasification reactions (He et al., 2022). These results indicate that CPW has particular advantages for hydrogen-rich syngas production relative to more graphitized woody chars. However, the same structural features that promote gasification reactivity may reduce the stability required for long-term carbon sequestration. Systematic comparisons of gasified CPW

char with other residues for combined syngas-biochar value chains are still limited, representing another gap in the literature.

Table 1 summarizes the approximate product yields associated with slow pyrolysis, fast pyrolysis, and gasification. Like other lignocellulosic feedstocks, slow pyrolysis of CPW maximizes solid char, fast pyrolysis favors liquid bio-oil, and gasification primarily yields syngas. What differentiates CPW is its high volatile and pectin content, which leads to (i) higher char yields than some green wastes at low temperatures, (ii) highly oxygenated bio-oils under fast pyrolysis, and (iii) exceptionally reactive chars under gasification. These features make CPW particularly attractive for applications where reactive, porous char and hydrogen-rich syngas are prioritized, but less ideal where very high fixed-carbon yields are needed.

Table 1 Approximate product yields from different thermochemical conversion processes.

Feedstock	Process	Temperature/Conditions	Product yield (wt% or mol%)	Reference
Lemon and orange	Slow pyrolysis	300–500 °C	Biochar: 31–53%; Bio-oil: 27%; Gas: 62%	Selvarajoo et al. (2022)
Lemon	Slow pyrolysis	300–500 °C	Biochar: 66.89%; Bio-oil: 16.66%; Gas: 54.6%	Abidi et al. (2023)
Sweet lime	Slow pyrolysis	900 °C	Biochar: 30%; Bio-oil: 35%; Gas: 38%	da Silva et al. (2022)
Orange	Fast pyrolysis	500 °C	Biochar: 27–33%; Bio-oil: 54.9%; Gas: 12–24%	Alvarez et al. (2018)
Orange	Steam gasification	750 °C, steam as oxidant	H ₂ : 58.8 mol%; CO: 25.34 mol%	Chiodo et al. (2017)

(4) Hydrothermal carbonization

HTC has recently emerged as a complementary route to slow and fast pyrolysis for converting wet CPW into carbonaceous solids. Unlike conventional pyrolysis, HTC operates in liquid water at relatively mild temperatures (typically 180–250 °C) under autogenous pressure, which allows direct processing of high-moisture CPW without energy-intensive drying. This makes HTC particularly attractive for the juice and beverage industries where peels are generated as wet slurries (Lei et al., 2021; Picone et al., 2021). However, HTC

generates not only solid fraction (commonly called hydrochar), but also carbon-rich process water and a minor gas phase, so carbon is distributed across three product streams rather than being concentrated in the solid fraction, as in biochar-oriented slow pyrolysis (Erdogan et al., 2015; Satira et al., 2021).

For orange and lemon peels, hydrochar yields are generally comparable to, or slightly greater than, char yields from low-temperature pyrolysis when expressed on a dry basis, typically in the range of 35–50 wt% depending on severity and the liquid/solid ratio (Fernandez et al., 2015; Picone et al., 2021). Picone et al. (2021) further reported that recycling HTC process water back into the reactor increases overall carbon recovery in the solid phase but can also accumulate inhibitory organics, indicating a trade-off between yield and process stability. Erdogan et al. (2015) and Satira et al. (2021) demonstrated that the aqueous phase contains substantial amounts of dissolved organics (sugars, organic acids, furans), which are potentially valuable for biogas production or as chemical precursors but are rarely quantified in citrus-specific studies. This highlights a major gap compared with the pyrolysis literature, where coproduct streams are usually less complex and more thoroughly characterized.

Structurally, CPW-derived hydrochars are typically more oxygen rich and less aromatized than conventional biochars are, with relatively low specific surface areas in their as-prepared state. Fernandez et al. (2015) reported that orange-peel hydrochar produced at 200 °C had limited porosity, but subsequent thermal or phosphoric acid activation increased the specific surface area to 300–620 m²/g and created coral-like porous networks that performed well in the adsorption of diclofenac, salicylic acid, and flurbiprofen. Similarly, Lei et al. (2021) reported that microwave-assisted HTC of orange peels, especially when catalyzed with citric acid, produced hydrochars with improved elemental compositions and relatively high heating values but still required further upgrading to compete with high-temperature biochars in terms of textural properties.

In addition to bulk powders, HTC enables more engineered architectures from citrus-derived precursors. Zhang and Zhou (2017) used citrus pectin to prepare carbon microspheres via HTC that, despite their modest specific surface area, exhibited very high methylene-blue uptake due to the abundance of carboxyl and aromatic sites. Li et al. (2023) employed a one-step hydrothermal route to obtain a magnetic Fe₃O₄/lemon-peel biochar nanocomposite with stable methylene blue adsorption over multiple cycles, illustrating how HTC can couple carbonization with in-situ nanoparticle formation. Durmaz and Şimşir (2025) extended the application of citrus-peel hydrochars to electrochemical energy storage, showing that KOH-activated HTC-derived carbons from four citrus species delivered specific capacitances of up

to 65.1 mF/cm² in double-layer supercapacitors. These studies collectively indicate that HTC-based materials are competitive not only as adsorbents but also as functional carbons for advanced applications.

Overall, the HTC of CPW is well aligned with the intrinsically high moisture content of citrus residues and opens a broader product portfolio (hydrochar, process-water organics, and gases) than classical pyrolysis. Moreover, most published work still focuses on laboratory-scale systems, single-target pollutants, and short-term tests. Systematic comparisons of carbon yield, energy efficiency, and long-term performance between HTC-derived hydrochars and conventional CPW biochars are rare, and the fate/valorization of the aqueous phase is often treated as a secondary issue. Addressing these gaps is essential for positioning HTC alongside slow pyrolysis and gasification as a mature, scalable route for citrus waste valorization.

3.1.2. Optimization of parameters

Numerous studies have examined the conversion of CPW into biochar under different operating conditions, largely motivated by its potential in wastewater remediation and pollutant adsorption (Selvarajoo et al., 2022). For other lignocellulosic biomasses, the efficiency of biochar as an adsorbent depends strongly on yield and on physicochemical properties such as surface area, pore structure, and surface functional groups, all of which are governed by pyrolysis parameters (Manyà, 2012; Ronsse et al., 2013). Compared with many woody and herbaceous feedstocks, CPW is particularly sensitive to temperature because of its high volatile content and lower lignin fraction. Temperature is widely recognized as the most critical parameter: lower pyrolysis temperatures (300–400 °C) favor higher biochar yields, whereas higher temperatures (> 500 °C) enhance carbonization and increase aromaticity and stability, but reduce yield (Selvarajoo et al., 2022). For lemon peel, Abidi et al. (2023) reported yields of up to 66.9% at 300 °C, which decreased substantially at higher temperatures. In contrast, da Silva et al. (2022) demonstrated that sweet lime peel subjected to pyrolysis at 900 °C yielded only ~30% char but with more fixed carbon and an improved surface area. Such trends parallel those observed for other lignocellulosic biomasses, yet the rate of yield loss with temperature appears steeper for CPW because of more extensive devolatilization and secondary cracking (Mohd Hasan et al., 2019).

The type of thermochemical process further influences product distributions. Slow pyrolysis of orange peels at 300–500 °C provides a solid-dominated output, whereas fast pyrolysis at ~500 °C favors liquid bio-oil, yielding ~55% oil with only 27–33% biochar (Alvarez et al., 2018). In contrast, steam gasification of orange peels at 750 °C generated syngas

with a high hydrogen content (58.8 mol%) and reduced the amount of solid residue (Chiodo et al., 2017). These results indicate that parameter optimization for CPW cannot be generalized to woody biomass alone; the process must be tuned depending on whether the primary objective is high-yield biochar, reactive biochar for catalysis, or gaseous energy carriers.

Feedstock variability adds another layer of complexity. Biochars produced from lemon, mandarin, orange, and grapefruit peels and present clear differences in production yield, moisture content, ash content, and specific surface area (Table 2). The lemon peel biochar had a relatively low ash content and favorable moisture levels, whereas the orange peel tended to generate chars with relatively high ash fractions. Across all citrus types, CPW-derived biochars presented specific surface areas of approximately 200–500 m²/g, pore volumes of 0.10–0.25 cm³/g, and carbon contents of approximately 55–80%, with pH values ranging from slightly acidic to neutral (Güzel and Akpınar, 2019). These values are broadly comparable to those reported for many agricultural residue biochars but are achieved at moderate pyrolysis temperatures (400–500 °C), underscoring the suitability of citrus peels as a versatile biochar feedstock.

These comparisons highlight both the promise and the challenge of CPW: the material can be tuned to yield biochars with competitive textural properties, yet the strong dependence on citrus species, peel morphology, and process conditions makes it difficult to define a single typical CPW biochar. Optimizing these parameters is therefore essential, not only to maximize yield but also to tailor the physicochemical properties of CPW-derived biochar for specific applications. As summarized in Table 1, different thermochemical conditions result in distinct product distributions, demonstrating that parameter optimization influences not only the yield but also the suitability of biochar for various end uses, such as adsorption-based wastewater treatment, soil improvement, or energy production through bio-oil and syngas. Systematic cross-feedstock studies that compare CPW with other residues under identical pyrolysis conditions remain scarce. Such work would be valuable for quantifying whether the higher reactivity and ease of pore development in CPW biochar can offset its lower maximum carbon yields relative to high-lignin woody feedstocks.

Table 2 Reported yields and key properties of citrus peel waste-derived biochars.

Feedstock	Pyrolysis temperature (°C)	Yield (wt%)	Moisture (wt%)	Ash (wt%)	Specific surface area (m ² /g)	Reference
Lemon	500	2.06	7.25	7.23	300–500	Güzel and Akpınar (2019)

	300–700	31–53	~4–7	~2–8	Not available	Selvarajoo et al. (2022)
Mandarin	400	3.92	6.49	3.31	250–450	Güzel and Akpınar (2019)
	900	30	3.19	11.85	3.3	da Silva et al. (2022)
Orange	450	2.33	7.73	9.01	200–400	Güzel and Akpınar (2019)
	300–700	31–53	~4–7	~2–8	Not available	Selvarajoo et al. (2022)
	900	30	3.27	8.62	2.7	da Silva et al. (2022)
Grapefruit	500	2.68	8.06	4.82	280–480	Güzel and Akpınar (2019)
Rangpur lime	900	30	4.81	12.01	0.2	da Silva et al. (2022)
Sweet lime	900	30	4.20	10.51	1.9	da Silva et al. (2022)

3.1.3. Physicochemical properties

The physicochemical properties of biochar, including surface area, pore size distribution, surface functional groups, proximate composition, and thermal stability, are key determinants of its performance in environmental applications. These characteristics are controlled by both the feedstock type and pyrolysis parameters (Gai et al., 2014). Compared with biochars derived from other lignocellulosic biomasses, CPW-based biochars generally present greater oxygen functionality, easily developed porosity, and relatively moderate carbon contents, traits that can be advantageous for adsorption but may limit long-term stability.

(1) Surface area and pore structure

Pyrolysis temperature and feedstock type strongly influence the porosity of biochar, which in turn governs its adsorption capacity. For CPW, Selvarajoo et al. (2022) reported that increasing the temperature promoted pore development and improved the specific surface area, similar to the trends observed in woody and herbaceous biochars. However, because citrus peels contain high levels of pectin and other thermally labile components, pore formation tends to occur at lower temperatures than in high-lignin wood. Encinar et al. (2001) reported pore sizes approximately 20–30 μm for typical woody biochars (obtained at 900 $^{\circ}\text{C}$), whereas citrus

peel-derived biochars displayed a broader pore size range of 5–70 μm (obtained at 300–700 $^{\circ}\text{C}$) (Selvarajoo et al., 2022), suggesting a more heterogeneous pore network. Recent work by Cao et al. (2023) demonstrated that surface modification of orange peel biochar (generated at 900 $^{\circ}\text{C}$) increased the specific surface area from 784 to 1102 m^2/g , accompanied by the formation of micropore network (1.49 to 1.69 nm), responsible for their high specific surface areas. These values are comparable to, or greater than, those reported for activated biochars derived from many other agricultural residues. The ease with which CPW biochar develops microporosity during activation indicates that this feedstock is particularly responsive to textural engineering, making it attractive for applications where a high surface area and controlled pore size are critical.

(2) Functional groups

The surface chemistry of CPW-derived biochar is typically rich in oxygenated functional groups owing to the high polysaccharide and pectin contents of the raw peel. The Fourier transform infrared spectra (FTIR) commonly display $-\text{OH}$ stretching at 3400–3440 cm^{-1} , $-\text{CH}_2-$ stretching at 2800–2900 cm^{-1} , COOH groups at 1620–1640 cm^{-1} , $\text{C}=\text{O}$ stretching at 1420–1440 cm^{-1} , and $\text{C}-\text{O}-\text{C}$ vibrations at 1040–1068 cm^{-1} (Adeniyi et al., 2022; da Silva et al., 2022). Selvarajoo et al. (2022) reported pronounced oxygenic peaks for citrus peel biochar produced at 500 $^{\circ}\text{C}$, which weakened at 700 $^{\circ}\text{C}$, indicating the progressive loss of surface functional groups at higher carbonization temperatures. Zhao et al. (2018) observed similar peaks for pomelo peel biochar, $\text{C}=\text{C}$ at 1616 cm^{-1} , $\text{C}=\text{O}$ at 1700 cm^{-1} , and $\text{O}-\text{H}$ at 3127 cm^{-1} , confirming the abundance of hydroxyl, carboxyl, and carbonyl groups that promote interactions with metal ions and organic pollutants. Ahmadian et al. (2023) reported that lemon peel biochar with abundant micropores and oxygen-containing groups effectively adsorbed $\text{Cr}(\text{VI})$ and Acid Orange 7 dye. Compared with biochars derived from more lignin-rich feedstocks, CPW biochars often start with a higher density of such polar functional groups, reducing the extent of chemical activation needed to achieve high affinity for many aqueous contaminants. Table 3 summarizes the characteristic FTIR bands reported for various citrus peel biochars.

Table 3 Functional groups of citrus peel waste-derived biochar identified via Fourier transform infrared spectroscopy.

Feedstock	Vibrational bands (cm^{-1})	Assigned functional group/compound	Reference
Orange	O–H (3450)	Hydroxyl groups	

	C-H (2853–2926)	Aliphatic groups	Cao et al. (2023)
	C=O/C=C (1632)	Carbonyl/Aromatic	
	C-O (1035)	Alcoholic and carboxylic acid	
	C-H (800)	Aromatic	
Orange, mandarin, rangpur lime, sweet lime	O-H (3420)	Hydroxyl groups	da Silva et al. (2022)
	C-H (2854–2926)	Aliphatic groups	
	C=O (1645–1745)	Carbonyl groups	
	C=C (1512)	Aromatic ring	
	C-O (1242)	Acetyl groups	
	C-O (1055)	Alcohol (cellulose/hemicellulose)	
Lemon	O-H (3340)	Hydroxyl groups	Li et al. (2023)
	C-H (2930)	Aliphatic groups	
	C=O (1700)	Carbonyl groups	
	C=C (1320)	Aromatic ring	

(3) Proximate analysis

Proximate compositions (moisture, volatile matter, ash, and fixed carbon) provide key insight into the stability and reactivity of CPW-derived biochars. As summarized in Table 4, Selvarajoo et al. (2022) reported that for mixed orange-lemon peel biochars (60 min, heating rate 5 °C/min, under N₂), increasing the pyrolysis temperature from 300 to 700 °C reduced volatile matter from 35.99 to 7.52 wt% and increased fixed carbon from 58.08 to 78.36 wt%, while moisture content remained relatively low ($\approx$ 4–7 wt%) and the ash content rose from 1.95 to 7.97 wt%. These trends reflect progressive devolatilization and aromatic condensation, yielding more carbon-rich and thermally stable chars at higher temperatures. In a complementary study, da Silva et al. (2022) reported that individual citrus peels (orange, mandarin, rangpur lime, and sweet lime) pyrolyzed at 900 °C for 15 min under N₂ (5 °C/min) produced biochars with very low volatile matter (6.68–8.74 wt%) and high fixed-carbon contents (79.25–84.70 wt%), together with appreciable ash fractions (8.62–12.01 wt%). Overall, Table 4 illustrates that CPW biochars can span a wide range of fixed-carbon contents ($\approx$ 58–85 wt%) and volatile fractions ($\approx$ 7–36 wt%) depending on citrus species and process severity; low-moderate temperatures yield more reactive, volatile-rich chars, whereas severe conditions (900 °C) generate highly carbonized materials suitable for long-term carbon sequestration and further activation. In general, CPW-derived biochars tend to retain higher volatile contents than many woody biochars under comparable conditions do, which is consistent with their often-higher reactivity and susceptibility to further activation or oxidation.

Table 4 Proximate analysis of citrus peel waste-derived biochar.

Feedstock	Pyrolysis temperature (°C)	Pyrolysis condition	Moisture content (wt%)	Volatile matter (wt%)	Ash content (wt%)	Fixed carbon (wt%)	Reference
Orange and lemon	300	60 min, heating rate = 5 °C/min, under N ₂ gas	3.98	35.99	1.95	58.08	Selvarajoo et al. (2022)
	400		4.17	29.97	3.52	62.34	
	500		6.48	13.25	2.50	77.77	
	600		7.35	9.61	1.25	81.79	
	700		6.15	7.52	7.97	78.36	
Orange	900	15 min, heating rate = 5 °C/min, under N ₂ gas	3.27	6.68	8.62	84.70	da Silva et al. (2022)
Mandarin			3.19	7.78	11.85	80.49	
Rangpur lime			4.81	8.74	12.01	79.25	
Sweet lime			4.20	8.12	10.51	81.38	

(4) Thermal stability

Thermogravimetric analyses of citrus peels and the resulting biochars revealed three decomposition stages: (i) moisture removal (30–110 °C), (ii) active pyrolysis dominated by hemicellulose and cellulose degradation (180–360 °C), and (iii) secondary decomposition and slow lignin degradation (280–360 °C and up to ~900 °C) (Selvarajoo et al., 2022; Lee et al., 2013; Liu et al., 2014). The relatively sharp mass-loss events associated with hemicellulose and pectin highlight the narrower process window for CPW than for some woody feedstocks, which exhibit broader degradation profiles. High fixed-carbon contents and gradual weight-loss profiles at elevated temperatures are indicative of improved stability for long-term environmental applications, but CPW biochars generally remain more reactive than highly graphitized woody chars. Overall, CPW-derived biochars combine moderate carbon contents with high oxygen functionality, readily develop porosity, and have relatively high reactivity. These traits make them particularly attractive for adsorption and catalytic applications in water and soil systems, while also pointing to trade-offs in long-term stability compared with more graphitized biochars. The current literature still lacks comprehensive cross-comparisons of CPW biochars with other lignocellulosic biochars under harmonized conditions, which represents a key knowledge gap that future studies should address.

3.2. Surface modification of citrus peel waste-derived biochar

To improve the performance of CPW-derived biochar in environmental and agricultural applications, a range of posttreatment strategies have been explored. Unmodified biochars often have limitations such as a moderate specific surface area, suboptimal porous structure, and insufficient density of reactive functional groups, which can restrict their affinity for specific contaminants or nutrients. Physical and chemical activation methods can substantially reshape these properties by adjusting the micro- and mesoporosity, surface charge, and abundance of oxygen- and heteroatom-containing groups (Ahmed et al., 2016). Common approaches include steam or CO₂ activation, thermal treatment under controlled atmospheres, acid or alkali washing, and impregnation with metal salts or metal oxides. In addition to improving contaminant retention, these modifications can increase the cation-exchange capacity and nutrient content, thereby increasing the agronomic value of CPW-derived biochar in soils (Hu et al., 2023).

Compared with the broad literature on biochar from woody or crop residues, systematic studies that link specific modification conditions to changes in the physicochemical properties of CPW-based biochars are still limited. Existing works often report improved adsorption behavior but provide only partial discussion of how pore development, surface chemistry, and mineral phases evolve during modification. The following subsections therefore focus on how different modification routes alter the structural and surface characteristics of citrus-based biochars, while their adsorption performance is discussed separately in the application sections.

3.2.1. Physical modification

Physical modification primarily relies on heat and gaseous agents (e.g., steam, CO₂, or O₃) to tailor the pore structure of biochar without directly introducing new chemical functionalities (Cha et al., 2016; Sajjadi et al., 2018). Under controlled gasification conditions, these agents react with the carbon matrix, widening existing micropores and creating additional mesopores; this typically increases the specific surface area and total pore volume, which are key parameters for sorption and catalytic processes (Sizmur et al., 2017).

In the context of citrus residues, steam (and chemical-thermal) activation has been applied to orange albedo biochar impregnated with ZnCl₂. Adeniyi et al. (2022) reported that such treatment produced a more developed porous network and altered the FTIR signatures of surface functional groups, indicating interactions between zinc species and lignocellulosic domains in the char (Romero-Cano et al., 2017). These changes suggest that physical activation can simultaneously enhance textural properties and subtly reorganize surface chemistry, even when no new functional groups are deliberately grafted.

Insights from noncitrus systems further clarify mechanisms that are likely relevant for CPW. For example, Shim et al. (2015) reported that steam activation of *Miscanthus* biochar substantially increased the specific surface area while leaving the overall pattern of functional groups largely unchanged. These findings supports the view that physical activation is the most effective tool for engineering pore architecture, including micropore development, mesopore widening, and increased surface accessibility, whereas targeted adjustments of surface chemistry generally require subsequent chemical modifications. In citrus peel-derived biochars, dedicated comparative studies between purely physical activation and combined physical-chemical routes are still scarce, representing an important gap for optimizing modification strategies for specific end-use applications.

3.2.2. Chemical modification

Chemical modification of CPW-derived biochar involves the use of acids, bases, or functional molecules to engineer both porosity and surface chemistry. Compared with purely physical activation, chemical treatments can simultaneously increase the specific surface area, tailor the pore structure, and introduce specific functional groups, making them highly effective for preparing biochars targeted at particular classes of contaminants (Wang et al., 2019).

(1) Acid and base treatments

Acidic treatments are commonly used to remove inorganic impurities (e.g., carbonates and metal oxides) and to introduce or enrich oxygen-containing groups such as carboxyl and phenolic moieties. Reagents including HCl, H₂SO₄, HNO₃, H₃PO₄, oxalic acid and citric acid have been widely applied (Rajapaksha et al., 2016). For pomelo peel biochar, Wei et al. (2022) reported that H₃PO₄ activation promoted extensive hydrolysis of ester groups in pectin and generated additional aromatic carboxylic sites in lignin, as evidenced by FTIR and elemental analysis. These changes translated into increased surface acidity and improved dispersion of micropores, features that favor ionic dye uptake in later applications.

Similarly, H₂SO₄ treatment of orange peel biochar leaches ash components and opens blocked pores, resulting in a more homogeneous micro-mesoporous structure and increasing the density of –SO₃H and –COOH groups on the surface (Jawad et al., 2019). On the alkaline side, activation with KOH or NaOH typically enlarges micropores and creates new mesopores while also generating additional oxygenated functionalities through partial oxidation of the carbon matrix (Wang et al., 2019). Tran et al. (2025) demonstrated that KOH-modified pomelo biochar presented a greater specific surface area and more developed pore volume than did its

raw counterpart, along with more basic surface sites; these features collectively supported multiple adsorption mechanisms such as pore filling and π - π interactions in the subsequent removal of dyes and antibiotics.

Across these studies, a consistent trend has emerged: CPW-derived biochars respond strongly to acid/base activation, achieving textural properties comparable to or exceeding those of many conventional biomass biochars, but with a higher density of accessible oxygenic groups. Table 5 summarizes representative changes in surface area, pore volume, and qualitative functional group characteristics for acid- and base-modified CPW-derived biochars. However, systematic comparisons across different citrus species and activation protocols are still scarce, making it difficult to derive generalized structure-property relationships.

(2) Functionalization with amine, thiol, and carboxyl groups

Beyond bulk acid/base activation, more advanced functionalization strategies involve the grafting of nitrogen- or sulfur-containing ligands onto CPW-derived biochar to target specific contaminants. Such treatments generally increase the number of strong coordination sites and shift the surface charge, thereby enhancing the affinity toward metal cations and certain organic molecules.

Huang et al. (2021) functionalized pomelo peel biochar with 3-amino-5-mercapto-1,2,4-triazole (AMT), introducing both -NH and -SH groups as confirmed by FTIR and X-ray Photoelectron spectroscopy (XPS). Compared with the pristine materials, the modified biochar displayed a higher nitrogen and sulfur content and a more positively charged surface at circumneutral pH, conditions that favor inner-sphere complexation with Pb^{2+} . Eleryan et al. (2022) employed a two-step protocol in which mandarin peel was first carbonized using concentrated H_2SO_4 and then aminated with triethylenetetramine (TETA). This route produced a biochar with increased basicity, abundant amine groups, and improved dispersion of micropores, which together enhanced electrostatic attraction and complexation toward anionic dyes such as Acid Yellow 11.

Daffala et al. (2024) prepared FeCl_3 -treated lemon peel biochar, yielding a magnetic material with a moderately increased surface area ($111.45 \text{ m}^2/\text{g}$) and iron oxides finely dispersed within the pore network. The presence of Fe-O and Fe-O-C bonds not only imparted magnetic separability but also created additional surface sites for redox-active interactions.

Taken together, these examples show that the chemical functionalization of CPW-derived biochars moves them beyond generic carbonaceous sorbents toward more sophisticated materials with tailored surface chemistry and, in some cases, built-in separability or catalytic

activity. Table 5 compiles representative CPW-based materials modified via acid/base treatment and heteroatom functionalization, highlighting the associated trends in surface area, porosity, and key functional groups. Nevertheless, most studies report single-point modifications under specific conditions, and comparative datasets that link functionalization chemistry, textural properties, and long-term stability are still limited. This is an important knowledge gap for future research.

Table 5 Representative chemical modification methods for citrus peel waste-derived biochar and key textural/surface properties after modification.

Feedstock	Modified material/treatment	Specific surface area (m ² /g)	Pore volume/pore structure	Key functional groups/surface features	Reference
Pomelo	Phosphoric-acid-activated pomelo peel biochar (PPC)	877.3	Total pore volume 0.486 cm ³ /g; micropores 0.333 cm ³ /g; mesopores 0.153 cm ³ /g; micro–mesoporous, type-I/H4 isotherm	Surface enriched with P-containing species (P–O, P=O) and oxygenated groups; high C/O ratio and strongly developed micro–mesoporosity	Wei et al. (2022)
Orange	H ₂ SO ₄ -activated orange peel biochar	Not available	Microporous structure with increased pore volume vs. raw peel (quantitative specific surface area data not reported)	Stronger –OH, C=O and –COOH bands; surface becomes more acidic with more oxygenic sites	Jawad et al. (2019)
Pomelo	KOH-activated pomelo peel biochars (PBC300-Kx, PBC400-K4)	15.7–27.2	Micropore volumes 0.012–0.031 cm ³ /g; average pore diameter	KOH activation creates more disordered carbon, higher basicity and	Tran et al. (2025)

			2.2–5.4 nm; micro– mesoporous	abundant oxygenated groups; pH_{pzc} shifts toward near-neutral	
Pomelo	AMT- functionalized pomelo peel biochar (GP- AMT)	23.2	Type-IV isotherm; multiaperture mesoporous structure; pore size increases vs. raw peel but some pores blocked vs. carbonized precursor	Grafting of 3- amino-5- mercapto- 1,2,4-triazole introduces N- and S- containing ligands ($-NH_2$, $-C=N-$, $-C-S-$); zeta potential becomes more negative; isoelectric point decreases	Huang et al. (2021)
Mandarin	TETA-aminated mandarin peel biochar (MBT)	5.48	Total pore volume 0.016 cm^3/g ; mean pore diameter 11.61 nm; mesopore volume 0.0172 cm^3/g ; mainly mesoporous, many original pores blocked	Strong $-OH$ and new $-NH/-$ $N=C=O$ bands; N content ~16 wt%; amination yields largely nonporous carbon with discrete amine sites	Eleryan et al. (2022)
Lemon	$FeCl_3$ - impregnated magnetic lemon- peel biochar (MLPB)	111.45	Total pore volume 0.091 cm^3/g ; average pore diameter 4.65 nm; mesoporous, type-IV/H3 isotherm	Presence of Fe_3O_4 /iron- oxide phases ($Fe-O$); improved thermal stability; magnetic behavior	Daffala et al. (2024)

				enabling easy separation	
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3.2.3. Hybrid materials

Hybrid materials, in which CPW-derived biochar is combined with metal oxides, metal nanoparticles, or magnetic phases, have attracted increasing interest as multifunctional adsorbents and catalysts (Wang et al., 2019). In these systems, biochar provides a high-surface-area, conductive, and mechanically robust carbon scaffold, whereas the inorganic phase contributes additional active sites, redox activity, or magnetism.

Li et al. (2023) synthesized a Fe_3O_4 /lemon-biochar nanocomposite via a one-step hydrothermal route. The resulting hybrid exhibited a well-dispersed magnetic phase within the carbon matrix, as confirmed by transmission electron microscopy (TEM) and X-ray diffractometer (XRD), together with an increased specific surface area and the emergence of new mesopores relative to those of the pristine biochar. These features enabled efficient separation with an external magnet and improved the accessibility of adsorption sites in subsequent methylene blue removal experiments. Tran et al. (2021) prepared KOH-activated pomelo peel biochar doped with Ag nanoparticles. Microscopic and spectroscopic analyses revealed that silver nanoparticles were anchored within the pore channels and on the external surfaces, slightly decreasing the average pore size but increasing the number of high-energy adsorption/catalytic sites for the removal of organic pollutants (methyl blue, rhodamine B and methyl orange) (Tran et al., 2021).

The evidence from noncitrus systems supports similar trends. Snoussi et al. (2022) reported that Ag impregnation of olive-pit biochar generated a more porous structure and increased the catalytic degradation activity. Shaikh et al. (2021) reported that a Ag-biochar nanocomposite had a surface area up to 14-fold greater than that of its parent biochar, with a transition from predominantly macroporous to mesoporous texture. Kaushal et al. (2019) reported that Ag-decorated banana-peel biochar exhibited improved electrical conductivity and electrochemical response, attributes relevant for sensing and energy applications. These studies collectively suggest that similar benefits, which include a greater specific surface area, altered pore architecture, and additional catalytic or antimicrobial functionality, can be systematically exploited in CPW-derived hybrid biochars.

Green synthesis routes, such as the reduction of AgNO_3 with glucose or plant extracts (Kumar et al., 2016), further align hybrid CPW biochars with circular economy principles by minimizing reliance on hazardous reductants.

In summary, hybrid modification transforms CPW-derived biochars into multifunctional platforms that couple adsorption with catalysis, antimicrobial activity, or easy magnetic recovery. The detailed adsorption capacities and removal efficiencies of these hybrids toward heavy metals and organic pollutants are presented in Section 3.3 (Tables 6 and 7). Here, the key message is that integrating inorganic phases markedly reshapes the textural and surface-chemical landscape of citrus biochars. Systematic comparisons between different hybridization strategies and their impacts on long-term stability and recyclability remain an open research frontier.

3.3. Application of CPW-derived biochar

CPW-derived biochars and their modified variants have been applied across several domains of environmental remediation, most notably for the removal of heavy metals and organic contaminants from water, as well as for nutrient control and soil amendment (Sections 3.3.4–3.3.5). Unlike many generic lignocellulosic biochars, citrus-based materials often combine high densities of oxygen-containing functional groups with tunable pore structures resulting from targeted activation (Sections 3.1–3.2). This section focuses on adsorption-based applications, emphasizing how specific preparation and modification routes translate into improved pollutant removal performance and where important research gaps remain.

3.3.1. Heavy metal removal

Heavy metal contamination in wastewater poses severe risks to human health and ecosystems, and has therefore been a primary target for CPW-derived adsorbents. Owing to the abundance of carboxyl, hydroxyl and other oxygenic groups, even raw or minimally treated citrus peels can complex with metal ions, whereas carbonization and further modification increase the stability, surface area and selectivity.

Unmodified or simply carbonized peels already show competitive performance. Bhatti et al. (2016) reported that dried CPW biomass removed Zr^{2+} ions with a capacity of 42.0 mg/g, indicating the potential for the treatment of radioactive nuclides. Sweet lemon peel-derived biochar produced via slow pyrolysis achieved 97.1% removal of Pb^{2+} from battery manufacturing effluent (Poonam and Kumar, 2020), and lemon peel activated carbon reached 89.2% Pb^{2+} removal from e-waste bioleachate (Divahar et al., 2024). These values are comparable to, or better than, many reported values for biochars from crop residues or forestry wastes, despite the relatively simple preparation steps.

More sophisticated modification strategies, as discussed in Section 3.2, further increase heavy metal uptake. For example, Huang et al. (2021) functionalized pomelo peel biochar with AMT, which markedly increased the density of N/S donor sites and achieved Pb^{2+} capacities (~ 420 mg/g) that exceeded those of most conventional lignocellulosic biochars. Nanofibrillated cellulose derived from *Citrus sinensis* bran and its Ag-nanoparticle composite also displayed enhanced performance: Cr^{6+} removal reached 47% with NFC alone and 47% (Cr^{6+}) plus 83% (Cd^{2+}) with Ag-NFs (Tavker et al., 2021). These examples illustrate how CPW's pectin-rich, oxygenated backbone provides a favorable platform for chemisorption-type interactions once appropriately functionalized.

The green synthesis routes also highlight the dual valorization of CPW. Aboelghait et al. (2024) used Murcott mandarin peel extracts as reducing and stabilizing agents to form Ag nanoparticles, achieving a Pb^{2+} uptake of 42.7 mg/g, whereas the solid residue from the synthesis still adsorbed 6.6 mg/g Pb^{2+} . Orange peel cellulose beads produced via acid/alkali treatment and bleaching attained high removal efficiencies for Pb^{2+} (98.3%) and Cd^{2+} (93.9%) and more moderate values for Cr^{6+} (33.5%) (Rahman et al., 2023).

Table 6 summarizes representative CPW-based adsorbents for heavy metal removal, incorporating both pristine and chemically modified materials. Overall, CPW-derived adsorbents reach Pb^{2+} capacities ranging from tens to several hundreds of mg/g and show strong affinity for Cd^{2+} , Cu^{2+} and Zr ions. Compared with many other biomass-derived biochars, citrus-based systems stand out where tailored functionalization (e.g., AMT, amine or nanoparticle grafting) is applied. Nevertheless, most studies still rely on single-metal batch tests with synthetic solutions; competitive sorption in multicomponent real wastewaters, long-term regeneration, and column-scale demonstrations remain key gaps that must be addressed before large-scale deployment.

Table 6 Applications of citrus peel waste-derived adsorbents for heavy metal removal.

Feedstock	Preparation/Modification method	Adsorbent type	Application medium	Target metal	Adsorption capacity/Removal efficiency	Reference
Murcott mandarin	Green synthesis of Ag-NPs	Ag nanoparticles (Ag-NPs)	Metal industrial wastewater	Pb^{2+}	42.7 mg/g	Aboelghait et al. (2024)
Murcott mandarin (residue)	Filtration residue from Ag-NP synthesis	Solid residue (MM-SR)	Metal industrial wastewater	Pb^{2+}	6.6 mg/g	Aboelghait et al. (2024)
Citrus	Drying and grinding	Raw biomass	Aqueous solution	Zr^{2+}	42.0 mg/g	Bhatti et al. (2016)
Sweet lemon	Slow pyrolysis	Biochar	Battery manufacturing effluent	Pb^{2+}	97.1% removal	Poonam and Kumar (2020)

Tahiti lemon	Thermochemical with ZnCl ₂ (550 °C)	ZnCl ₂ -activated biochar (LPZn)	Synthetic wastewater	Cu ²⁺	28.9 mg/g,	Pérez et al. (20230)
Lemon	Thermal activation	Activated carbon	E-waste bioleachate	Pb ²⁺	89.2% removal	Divahar et al. (2024)
Orange	Acid/alkali treatment, bleaching → fibers	Orange peel cellulose (OPC) beads	Synthetic wastewater	Pb ²⁺ , Cr ⁶⁺ , Cd ²⁺	98.3% (Pb ²⁺), 93.9% (Cd ²⁺), 33.5% (Cr ⁶⁺)	Rahman et al. (2023)
Citrus sinensis (bran)	Alkali and acid hydrolysis	Nanofibrillated cellulose (NFC)	Simulated pharmaceutical effluent	Cr ⁶⁺	47% removal	Tavker et al. (2021)
Citrus sinensis (skins)	NFC + Ag nanoparticle composite	Ag-NPs/NFC composite	Simulated pharmaceutical effluent	Cd ²⁺ , Cr ⁶⁺	83% (Cd ²⁺), 47% (Cr ⁶⁺)	Tavker et al. (2021)
Pomelo	AMT functionalization (3-amino-5-mercapto-1,2,4-triazole)	AMT-modified biochar	Aqueous solution	Pb ²⁺	~420 mg/g	Huang et al. (2021)

3.3.2. Organic contaminant adsorption

CPW-derived adsorbents have also been widely investigated for the removal of organic contaminants, including synthetic dyes, pharmaceuticals, oils, and organic solvents. Their performance depends on the combination of a π -conjugated carbon framework, tunable micro-mesoporosity, and surface functionalities such as hydroxyl, carboxyl, and phenolic groups, which together enable interactions like π - π stacking, hydrogen bonding, hydrophobic partitioning, and electrostatic attraction (Li et al., 2023; Kapoor et al., 2024). The dominant mechanisms underlying these processes are discussed in detail in Section 3.3.3.

Unmodified citrus peel powder can remove colored organics. Topare et al. (2020) reported a maximum rhodamine B uptake of 125 mg/g using sun-dried, powdered citrus peels, highlighting the inherent sorption capacity of the native biopolymer matrix. However, the adsorption capacity was greater for citrus peel biochar. Citrus pectin-derived carbon microspheres via HTC achieved an outstanding methylene blue adsorption capacity of 979.3 mg/g (Zhang and Zhou, 2017). HTC followed by the thermal or chemical activation of orange peels produces hydrochars with surface areas of 300–620 m²/g; these materials effectively adsorb pharmaceuticals such as diclofenac sodium, salicylic acid and flurbiprofen, with capacities of 0.211, 0.66 and 0.83 mmol/g, respectively (Fernandez et al., 2015). These values are comparable to or greater than those for many noncitrus hydrochars prepared under similar conditions, indicating that the high oxygen content of CPW does not preclude the development of well-defined porosity.

Chemical and hybrid modifications (Section 3.2) further tailor interactions with organics. Wei et al. (2022) reported that H₃PO₄-activated pomelo biochar was enriched with carboxyl and phosphate groups, which increased ionic dye uptake through electrostatic attraction and complexation. H₂SO₄ treated orange peel biochar exhibited increased aromaticity

and surface acidity, favoring π - π and electrostatic interactions with cationic dyes such as methylene blue (Jawad et al., 2019). KOH-activated pomelo biochar has developed a highly microporous/mesoporous structure that facilitates pore filling and π - π interactions for methylene blue and oxytetracycline (Tran et al., 2025).

Magnetic and hybrid systems provide additional benefits in terms of recovery and multifunctionality. Li et al. (2023) fabricated Fe₃O₄/lemon-peel biochar nanocomposites via hydrothermal synthesis; the resulting material combined a moderate surface area with strong magnetization, enabling efficient methylene blue adsorption (26.4 mg/g) and easy magnetic separation. Daffala et al. (2024) prepared FeCl₃-derived magnetic lemon biochar with a surface area of 111 m²/g that removed methyl orange with 90.9% efficiency, whereas Eleryan et al. (2022) obtained TETA-aminated mandarin biochar with a capacity of 384.6 mg/g for Acid Yellow 11, benefitting from enhanced electrostatic attraction. Magnetic hydrophobic/superoleophilic sorbents synthesized from orange peels and Fe₃O₄-polydimethylsiloxane removed 5–7 g of oils or organic solvents per gram of sorbent (Singh et al., 2017), illustrating the versatility of CPW-derived materials beyond aqueous dyes and pharmaceuticals.

Table 7 shows representative examples of citrus-based adsorbents for organic contaminant removal. A clear pattern emerges: unmodified or simply carbonized peels achieve modest capacities, whereas chemically activated, aminated or hybrid materials reach the upper range of performances (> 300–900 mg/g for dyes and nearly 1 mol/kg for pharmaceuticals). Despite these promising results, most studies are still conducted in single-solute systems; data on competitive adsorption, fouling, and regeneration over many cycles are limited. Furthermore, the mechanistic understanding, particularly the relative contributions of π - π interactions, hydrogen bonding and electrostatic forces, remains incomplete, suggesting fertile ground for future combined experimental modeling work.

Table 7 Adsorption performance of citrus peel waste-derived adsorbents for organic contaminant removal.

Feedstock	Preparation/Modification method	Adsorbent type	Application medium	Target organic	Adsorption capacity/Removal efficiency	Reference
Orange	Hydrothermal carbonization; thermal/chemical activation	Hydrochars, activated hydrochars	Synthetic wastewater	Diclofenac sodium (DFS), salicylic acid (SA),	0.211 mmol/g (DFS), 0.66 mmol/g (SA), 0.83 mmol/g (FP)	Fernandez et al. (2015)

				flurbiprofen (FP)		
Lemon	Hydrothermal carbonization; Fe ₃ O ₄ magnetic modification	Magnetic lemon peel-derived biochar nanocomposite (Fe ₃ O ₄ /LP-biochar)	Synthetic wastewater	Methylene blue	26.36 mg/g	Li et al. (2023)
Orange	Drying, powdering; Fe ₃ O ₄ incorporation + polydimethylsiloxane coating	Magnetic hydrophobic/superoleophilic sorbent (MOPPs)	Synthetic water	Diesel oil, engine oil, decane, hexadecane, toluene, olive oil, vegetable oil	5.11–6.90 g/g (oil and solvents)	Singh et al. (2017)
Citrus pectin	Hydrothermal method	Citrus pectin-derived carbon microspheres (CPCMs)	Synthetic water	Methylene blue	979.3 mg/g	Zhang and Zhou (2017)
Citrus	Sun-dried, powdered, sieved	Citrus peel powder	Synthetic water	Rhodamine B	125 mg/g	Topare et al. (2020)
Pomelo	Phosphoric acid activation (H ₃ PO ₄)	H ₃ PO ₄ -activated biochar	Synthetic dye solutions	Methyl orange, rhodamine, crystal violet	Enhanced dye adsorption; mechanism via ester hydrolysis and carboxyl formation	Wei et al. (2022)
Orange	Sulfuric acid activation (H ₂ SO ₄)	H ₂ SO ₄ -activated biochar	Synthetic dye solution	Methylene blue	208.3 mg/g	Jawad et al. (2019)
Lemon	Magnetic biochar via FeCl ₃ impregnation	Magnetic lemon biochar	Synthetic dye solution	Methyl orange	90.87% removal; surface area 111.45 m ² /g	Daffala et al. (2024)
Pomelo	KOH activation	KOH-activated biochar	Synthetic wastewater	Methylene blue, oxytetracycline	268 mg/g (MB); 95.6 mg/g (OTC)	Tran et al. (2025)
Mandarin	Dehydration with H ₂ SO ₄ ; amination with TETA	TETA-aminated biochar	Synthetic dye solution	Acid Yellow 11	384.6 mg/g; high reusability	Eleryan et al. (2022)
Tahiti lemon	Thermochemical with ZnCl ₂ (550 °C)	ZnCl ₂ -activated biochar (LPZn)	Synthetic wastewater	Congo red	618.4 mg/g	Pérez et al. (2023)

3.3.3. Mechanisms of contaminant removal by CPW-derived biochar

Due to the limited number of mechanistic studies on CPW-derived biochars, much of the current understanding of adsorption pathways is inferred from broader biochar literature, with only a few works directly examining citrus-based systems. Nevertheless, the available evidence suggests that several processes act in parallel. Hydrogen bonding occurs between surface –OH/–COOH groups on biochar and polar functional groups on dyes and other

organics, as indicated by FTIR shifts of hydroxyl and carbonyl bands before and after adsorption (Inyang and Dickenson, 2015). The functional groups observed on CPW and its chars (carboxyl, phenolic hydroxyl, and ether groups) mainly originate from lignin and cellulose, and their shifts upon adsorption have been reported for orange-peel-derived biochars (Kalengyo et al., 2024).

Pore filling is another important contribution, whereby organic molecules occupy micro- and mesopores, driven largely by van der Waals forces; the relative proportions of micro- and mesopores therefore strongly influence uptake of small organic molecules (Aziz et al., 2025; Mandal et al., 2017). π - π interactions take place between the aromatic domains of biochar and π -electron systems in pharmaceuticals and dyes containing benzene rings, as evidenced by changes in C=C stretching bands and new peaks attributed to -COOH/-NH₂ after adsorption of textile organics on orange-peel biochar (Kalengyo et al., 2024; León et al., 2023). Hydrophobic interactions also contribute, with non-polar organics partitioning from the aqueous phase into the relatively hydrophobic carbon matrix; several studies have reported correlations between biochar hydrophobicity and adsorption of phenols and parabens (Xiang et al., 2020; León et al., 2023).

For ionic species, electrostatic interactions between charged pollutants and the pH-dependent surface charge of biochar are often critical. When the solution pH is above the biochar point of zero charge, negatively charged surfaces favor adsorption of cationic dyes and metal ions, whereas at low pH electrostatic repulsion can suppress uptake (Dong et al., 2011; Xu et al., 2011; Ahamd et al., 2015). Changes in ionic strength may either enhance or inhibit adsorption, depending on whether co-ions screen repulsive forces or compete for the same sites (Inyang and Dickenson, 2015). Finally, ion exchange between inorganic cations associated with the biochar surface (e.g. K⁺, Ca²⁺) and metal ions or other cationic contaminants in solution has been proposed as an additional pathway, with the extent of exchange controlled by surface morphology and hydrated ion size (Zhao et al., 2017; Shakoor et al., 2020). Overall, these mechanisms are broadly consistent with those reported for other lignocellulosic biochars, but detailed mechanistic studies dedicated to CPW systems remain scarce, representing an important research gap for future work.

3.3.4. Nutrient contaminant control

Excess nutrients particularly phosphate, nitrate, and ammonia, pose a complex environmental challenges. Although these nutrients are essential for plant growth and beneficial when returned to soils, their uncontrolled accumulation in wastewater accelerates

eutrophication, triggers algal blooms, and leads to oxygen depletion in aquatic ecosystems. As a result, the development of low-cost sorbents capable of efficiently removing nutrient species from water while allowing the possibility of nutrient recovery is an emerging priority. Owing to its pectin-rich matrix and abundance of hydroxyl and carboxyl functional groups, CPW provides a versatile platform for nutrient adsorption in various processed forms, including dried peels, activated carbon, and biochar.

Several studies have highlighted the strong intrinsic affinity of raw citrus peels for nutrient ions. The raw orange peels exhibited a phosphate adsorption capacity of approximately 4 mg/g, as reported by Abdelmadjid et al. (2025). Habchi et al. (2025) reported that only 50 mg of raw orange peel, that was only treated by drying at 105 °C for 2 h and grinded at room temperature, allowed removing 1.54 mg/g phosphate within 105 min, while simultaneously reducing biochemical oxygen demand and chemical oxygen demand, demonstrating cobenefits for organic matter removal. These findings underscore that even minimally processed CPW can act as a multifunctional adsorbent. In addition to raw peels, modified citrus peel-derived adsorbents show enhanced performance. Activated carbon synthesized from orange peels via ZnCl_2 activation achieved 86% nitrate removal under optimized conditions (Vijaya Kumar and Prasad Raju, 2020), with improved porosity and surface charge contributing to higher adsorption rates. Composite materials further extend this capability; an iron-chitosan composite integrated with orange peel-derived activated carbon reached a nitrate capacity of 263 mg/g and nearly complete removal efficiency (Amirsadat et al., 2024), emphasizing the importance of synergistic amine-metal interactions in nutrient sequestration.

Additional evidence supports the suitability of CPW-based materials for ammonium and nitrate capture in real water systems. Dey et al. (2021) demonstrated the complete removal of 1 mg/L-nitrate and 1 mg/L-ammonia from dried orange peels, although relatively high doses (2–4 g) were needed, indicating that raw peels may be more appropriate for low-cost, decentralized treatment than high-load systems. Moreover, CPW-derived biochar offers increased structural stability and tunability. Chen et al. (2022) reported that Ca/Zn-modified orange peel biochar achieved 52.96 mg/g phosphate adsorption, representing an eightfold increase over unmodified biochar, highlighting the role of engineered surface complexes (Ca–O–P, Zn–O–P) in enhancing phosphate affinity. Although current evidence indicates that CPW-derived biochars perform competitively with other lignocellulosic biochars, their naturally higher contents of calcium, potassium, and residual pectin structures may provide additional binding sites, particularly for phosphate, suggesting a compositional advantage in some nutrient adsorption applications.

While these studies confirm the strong potential of CPW-derived sorbents for nutrient removal, key research gaps remain. Most existing work is limited to batch systems under controlled laboratory conditions, with little understanding of long-term performance in high-strength or multicomponent wastewater. Comparative mechanisms for phosphate versus nitrate and ammonia uptake have not yet been well elucidated for CPW biochar systems, and the potential for nutrient-loaded CPW sorbents to be repurposed as slow-release fertilizers has been suggested but remains underexplored. Future research should therefore focus on mechanistic studies, regeneration cycles, field-scale validation, and technoeconomic analyses that consider both water quality improvements and circular nutrient recovery.

3.3.5. Soil amendments and carbon sequestration

Nutrient elements such as nitrogen and phosphorus are essential for soil fertility, microbial activity, and long-term crop productivity. When applied to soils in controlled amounts, these nutrients stimulate plant growth and increase soil organic matter accumulation. However, when the same nutrients accumulate in wastewater, they accelerate eutrophication and algal blooms, deteriorating water quality. This contrast underscores the importance of developing nutrient-retentive soil amendments that simultaneously improve soil health and prevent nutrient leaching into aquatic systems. CPW-derived biochar, enriched with pectin-derived oxygenated groups, minerals, and aromatic carbon structures, offers a multifunctional solution for both goals.

Several studies have demonstrated that CPW biochar improves soil physicochemical properties and enhances carbon sequestration capacity. CPW is naturally rich in pectin, limonene residues, phenolic compounds, and mineral nutrients such as calcium and potassium (Liu et al., 2021). These constituents give CPW-biochar a more functionalized surface than many conventional lignocellulosic biochars do. When applied to agricultural soils, CPW-biochar has shown consistently improved in soil organic matter and microbial activity. In citrus orchards, a 4% application of orange peel biochar increased soil organic carbon by 22.49%, reflecting its strong capacity to stabilize carbon pools (Hu et al., 2023). The same study revealed that coapplication of orange peel residue biochar (2.6%) with *Cipangopaludina chinensis* shell powder (1.3%) further increased microbial biomass carbon (+19.81%) and dissolved organic carbon (+64.88%), demonstrating synergistic effects on microbial activity and soil carbon cycling (Hu et al., 2023).

In addition to nutrient enhancement, CPW-derived biochar increases soil pH because liming effect contributes to improved soil chemical conditions, cation exchange capacity, and

enzymatic activity, and has been linked to reductions in CO₂ and N₂O fluxes (Sial et al., 2019). These environmental cobenefits stem from the aromatic, recalcitrant carbon structures formed during pyrolysis, which contribute to long-term carbon stabilization with residence times spanning decades to centuries.

Despite these advantages, research on the use of CPW biochar in soil systems remains limited compared with that on other biomass sources. Most findings are based on short-term or controlled experimental settings, and the long-term behavior of CPW-biochar under field conditions is insufficiently understood. Variability in pyrolysis temperature, particle size, and application rate can influence soil responses, and high mineral content may cause localized salinity increases at excessive dosages. Furthermore, standardized production protocols and field-scale carbon accounting methods for CPW-derived biochar are still limited. Overall, CPW-derived biochar is a promising dual-function amendment that enhances soil quality while contributing to carbon sequestration. Future research should prioritize long-term trials, dose optimization, and integrated assessments linking soil health, nutrient cycling, greenhouse gas mitigation, and practical agricultural outcomes.

3.3.6. Biomedical applications

Biomedical exploration of CPW-derived biochar is still in its infancy, yet early evidence suggests that pyrolyzed and hydrothermally carbonized CPW materials hold distinct potential in advanced therapeutic applications. Unlike raw citrus extracts or phytochemical fractions, which fall outside the scope of biochar-based technologies, CPW-derived biochar produced through HTC has the nanoscale architecture, surface functional groups, and colloidal stability required for biomedical use. The inherent pectin- and phenolic-derived oxygenated functionalities of citrus biomass facilitate postsynthesis modification, offering a unique advantage over many lignocellulosic feedstocks that require more aggressive chemical treatments to achieve similar surface chemistry.

The most advanced demonstration to date comes from the work of Iannazzo et al. (2022), who converted orange peel into nanobiochar (NBC) and engineered it as a targeted drug delivery platform. The resulting NBC displayed high dispersibility, tunable surface chemistry, and the capacity for ligand grafting (e.g., biotin, riboflavin), enabling selective uptake by lung cancer A549 cells and improved delivery of poorly soluble anticancer molecules. This study highlights not only the feasibility of turning CPW into functional nanocarbon materials but also the translational relevance of CPW-derived NBC in precision medicine, where its targeting ability and biocompatibility are critical.

Despite these promising findings, the biomedical potential of CPW-derived biochar remains under-explored. Current studies are restricted to in vitro settings, leaving major gaps in understanding regarding long-term cytotoxicity, biodistribution, biodegradation, immune system interactions, and clinical scalability. Unlike more mature carbon nanomaterials such as graphene or carbon nanotubes, CPW-based NBC has not yet undergone systematic evaluation of nanobio interactions or regulatory considerations. Furthermore, comparative studies assessing whether CPW-derived NBC offers performance advantages over NBC from other biomass feedstocks are virtually absent.

Overall, CPW-derived NBC represents an emerging and strategically important frontier for biomedical innovation within the domain of pyrolysis- and HTC-based materials. Continued research should focus on mechanistic nanotoxicology, ligand-surface interactions, pharmacokinetic behavior, and standardized synthesis protocols to advance CPW-based NBC from exploratory demonstrations toward clinically relevant therapeutic systems.

3.4. Challenges and future perspectives

3.4.1. Challenges in CPW valorization

The conversion of CPW into biochar represents a promising strategy for sustainable waste valorization and environmental remediation; however, multiple challenges continue to limit its reproducibility, scalability, and long-term environmental safety. These challenges can be categorized into five major domains: raw material variability, process optimization limitations, scale-up and cost issues, regeneration and environmental risks, and regulatory or supply chain constraints.

(1) Raw material variability

The intrinsic heterogeneity of CPW remains one of the most significant barriers to standardized biochar production. The physicochemical characteristics of citrus peels differ substantially among species such as lemon, orange, pomelo, and grapefruit, as well as across seasons and postharvest treatments (Teigiserova et al., 2021; Satari and Karimi, 2018). Variations in peel thickness, moisture content, and proportions of cellulose, hemicellulose, lignin, and pectin create inconsistent thermal decomposition profiles during pyrolysis (Selvarajoo et al., 2022). This results in large fluctuations in biochar yield, carbon content, pore structure, and functional groups. Furthermore, pesticide residues and agrochemicals commonly found on citrus peels can thermally degrade into potentially toxic compounds during pyrolysis, raising environmental and occupational health concerns (Ortelli et al., 2005). This variability

complicates process standardization, limits reproducibility, and challenges the establishment of uniform quality criteria for CPW-derived biochar.

(2) Process optimization limitations

The properties of biochar depend strongly on pyrolysis parameters, including temperature, heating rate, residence time, and activation agents. Achieving optimal surface area, porosity, and functional group availability often requires operating conditions that simultaneously reduce biochar yield. At elevated temperatures, excessive volatilization and secondary cracking reactions lower the solid output (Mohd Hasan et al., 2019; Ronsse et al., 2013; Selvarajoo et al., 2022). Additionally, the inherently high moisture content of CPW demands energy-intensive predrying. Poor feedstock storage may also promote microbial degradation, altering the chemical composition prior to conversion. Process optimization remains further complicated by seasonal biomass variability and the need for rapid, low-cost pretreatment strategies. In addition, the liquid and gaseous by-products from CPW pyrolysis, such as bio-oil and biogas, often suffer from instability and processing complexity, limiting their practical utilization (Wang et al., 2021). The development of predictive models and adaptive control systems is crucial for improving process consistency and addressing these limitations.

(3) Scale-up and cost issues

Although CPW-derived biochar is generally more cost-effective than conventional activated carbon is, its economic feasibility at the commercial scale remains uncertain. Large-scale production requires dedicated infrastructure, efficient logistics for biomass collection, and strict environmental compliance (Kiteto et al., 2025). A high moisture content increases drying and handling costs, whereas continuous reactor operation demands significant capital and operational investment. Related CPW-based processes such as bioethanol production have demonstrated favorable economic indicators (return on investment: 23.21–25.15%) (Kiteto et al., 2025). These results suggest that integrated biorefineries, which combine biochar production with value-added coproducts, may help improve profitability. Nonetheless, comprehensive technoeconomic analyses specific to CPW biochar systems are still lacking and represent an important research gap.

(4) Regeneration and environmental risk

While surface modifications, acid/base activation, metal oxide impregnation, and nanoparticle doping can significantly enhance adsorption performance (Nguyen Tan and Babel, 2025; Qiu et al., 2022; Sultana et al., 2022), these treatments may reduce stability under realistic conditions. Competing ions, pH variations, and natural organic matter often diminish the adsorption efficiency (Qiu et al., 2022; Rahman et al., 2023). Regeneration processes must prevent structural collapse and avoid the introduction of secondary pollutants to ensure sustained applicability (Aboelghait et al., 2024; Nguyen Tan et al., 2024). Concerns also arise regarding the potential leaching of metals or nanoparticles from modified biochar, long-term changes in soil or aquatic chemistry, and cumulative ecotoxicological effects (Divahar et al., 2024; Selvarajoo et al., 2022). Addressing these uncertainties requires standardized characterization protocols, comprehensive ecotoxicity studies, and systematic long-term assessments (Ha and Nguyen Tan, 2025; Hu et al., 2023).

(5) Regulatory, supply chain, and sustainability constraints

The deployment of CPW-derived biochar within a circular bioeconomy demands coordinated biomass sourcing systems, storage and transport infrastructure, and alignment with regulatory frameworks governing waste management and soil/water amendments (Kiteto et al., 2025). Achieving public acceptance requires transparent safety evaluations and stakeholder involvement throughout the innovation chain (Ha and Nguyen Tan, 2025). Although CPW-derived biochar provides benefits such as greenhouse gas mitigation, soil carbon enhancement, nutrient recovery, and pollution reduction (Sial et al., 2019), sustainable performance strongly depends on life cycle impacts, handling practices, and local environmental conditions. Further development of policies, certification schemes, and environmental performance metrics is essential for safe and responsible adoption.

Overall, CPW-derived biochar has strong potential for pollutant removal, soil amendment, and advanced applications (Sial et al., 2019). However, progress toward large-scale, reliable implementation requires addressing raw material variability, refining process optimization strategies, ensuring economic feasibility, mitigating environmental risks, and strengthening regulatory and supply chain systems. These challenges collectively define the critical research gaps that must be addressed for CPW valorization to mature into a sustainable and impactful circular bioeconomic strategy.

3.4.2. Future perspectives

Future advancements in CPW-derived biochar are expected to emerge from innovations in material modification, digital optimization, and sustainability integration. Enhanced modification strategies, including hybrid nanocomposites, biomolecule-assisted functionalization, and catalytic activation, offer promising pathways for tailoring surface chemistry, improving selectivity, and accelerating adsorption kinetics under diverse environmental conditions (Das and Panda, 2022; Shan et al., 2020). Importantly, future studies should incorporate advanced spectroscopic tools and computational modeling to reveal the underlying mechanisms governing adsorption, such as ion exchange, electrostatic interactions, complexation, and surface precipitation (Alam et al., 2018; Osman et al., 2023).

Digital innovation is expected to play a transformative role. Machine learning (ML) and artificial intelligence (AI) can efficiently predict biochar yield and physicochemical properties from pyrolysis parameters and feedstock composition, enabling real-time process optimization and quality control (Nighojkar et al., 2023). These tools also support digital twin systems for large-scale simulation and can identify potential coproducts to increase economic viability (Zhang, P. et al., 2024).

From a sustainability perspective, CPW-derived biochar aligns strongly with several United Nations SDGs (Shoudho et al., 2024). Notable contributions include improved wastewater treatment (SDG 6: Clean water and sanitation), waste reduction and resource recovery (SDG 12: Responsible consumption and production), and enhanced soil carbon sequestration with reduced greenhouse gas emissions (SDG 13: Climate action) (Shoudho et al., 2024; Patro et al., 2024). The integration of eco-design principles and circular bioeconomic frameworks will further strengthen the environmental and societal benefits of CPW valorization.

Overall, future progress requires a combined approach that merges advanced material engineering, digital optimization, scalability-oriented design, and sustainability assessment. Such integration will allow CPW-derived biochar to evolve from a promising waste-derived material to a viable, safe, and impactful technology for environmental remediation and circular economy transitions.

4. Conclusions

The sustainable utilization of CPW through biochar production offers a practical and impactful pathway for reducing agricultural waste burdens, mitigating environmental pollution, and advancing circular bioeconomic strategies. CPW-derived biochar has favorable physicochemical characteristics, including high porosity, abundant and diverse functional

groups, and tunable surface chemistry, which support the effective removal of heavy metals, organic pollutants, and nutrients. In addition to wastewater treatment, these materials also contribute to soil fertility enhancement, carbon sequestration, biomedical innovations, and other value-added applications. Despite their merits, several challenges remain. Variability in CPW composition and pyrolysis parameters can affect reproducibility, whereas scale-up requires investment in energy-efficient pretreatment, standardized quality control, and technoeconomic assessment. Moreover, potential environmental and health risks, such as nanoparticle release or long-term ecotoxicity from modified biochar, must be thoroughly evaluated. Future advancements in nanocomposite engineering, catalytic activation, and biomolecule-assisted functionalization are expected to improve adsorption selectivity and long-term stability. The integration of artificial intelligence and machine learning can further facilitate predictive optimization and process simulation for CPW-derived biochar technologies. Importantly, CPW valorization directly contributes to several SDGs:

- SDG 6 (Clean water and sanitation) which enable low-cost and efficient removal of contaminants from water systems;
- SDG 12 (Responsible consumption and production) by transforming citrus industry waste into high-value products within a circular resource framework;
- SDG 13 (Climate action) via carbon sequestration, reduced greenhouse gas emissions, and improved waste management practices.

In conclusion, CPW-derived biochar represents a sustainable, multifunctional, and economically viable material capable of converting abundant citrus waste into value-added products. Continued interdisciplinary efforts involving material science, environmental engineering, and policy development will be critical for unlocking the full potential of these abundant biowaste resources.

CRedit authorship contribution statement

Simron Rai: methodology, investigation, visualization, data curation, writing – original draft, writing – review and editing, funding acquisition. **Thong Nguyen Tan:** methodology, investigation, visualization, data curation, writing – original draft, writing – review and editing. **Visanu Tanboonchuy:** investigation, resources, writing – review and editing. **Sarttrawut Tulaphol:** visualization, writing – review and editing. **Seelawut Damrongsiri:** writing – review and editing. **Penradee Chanpiwat:** writing – review and editing. **Doan Pham Minh:** conceptualization, supervision, writing – review and editing, project administration. **Oriez Vincent:** conceptualization, writing – review and editing. **Nurak Grisdanurak:** resources,

writing – review and editing. **Mongkolchai Assawadithalerd:** supervision, writing – review and editing. **Pummarin Khamdahsag:** conceptualization, methodology, visualization, data curation, resources, writing – original draft, writing – review and editing, supervision, project administration, funding acquisition.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used ChatGPT (OpenAI) and Rebriq (AI automated language editing tool) to improve language, clarity, and readability of the text. After using this tool, the authors carefully reviewed and edited the content and take full responsibility for the final version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of Competing Interest

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- Evaluates citrus peel waste as a unique feedstock for producing high-value biochar.
- Compares how pyrolysis conditions shape carbon yield, porosity, and functional groups.
- Assesses modification strategies that enhance surface chemistry and reactivity.
- Identifies application trends and research gaps for citrus peel waste valorization.