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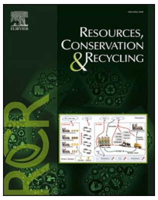

Review

Reclaiming cigarette butts: biorefinery technologies toward circular waste valorization

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ABSTRACT

Cigarette butts (CBs) are among the most abundant forms of anthropogenic litter, with about 5 trillion units discarded each year, corresponding to more than 800,000 tons of waste. Composed primarily of cellulose acetate (CA), accounting for 95% of the filter mass, CBs exhibit low biodegradability and act as carriers of toxic substances such as nicotine, heavy metals, and polycyclic aromatic hydrocarbons. Their persistence in the environment has raised growing concerns across terrestrial and aquatic ecosystems. This review critically examines the potential integration of CBs into circular waste management strategies through biorefinery technologies. Key processes include deacetylation to increase hydrolytic accessibility, enabling conversion into fermentable sugars for bioethanol production, as well as thermochemical routes like pyrolysis for fuel and activated carbon generation. Additional valorization options, such as enzymatic degradation and transformation into nanostructured carbon materials, are discussed with respect to their feasibility and environmental impact. Legislative gaps, technological barriers, and limited scalability are identified as major constraints to industrial implementation. Nonetheless, the inclusion of CBs as a non-conventional feedstock offers a promising opportunity to reduce the environmental footprint of CBs while recovering energy and materials within a biorefinery loop.

1. Introduction

CBs are the most discarded waste item globally, with an estimated 4.95 trillion individual butts polluting the environment each year (Howlader et al., 2024a). This amount corresponds to approximately 766,57 metric tons of toxic trash annually (Quit, 2024). CBs and filters constitute about 20% of the litter found on beaches, making them the most prevalent type of waste in these areas (Statistica.com, 2019). In urban settings, studies have reported densities of up to 130 CBs per square meter in some cities, 150 butts per kilometer along suburban roads, and 1,600 butts per 100 meters on beaches (Lakatos et al., 2024). Strong differences in plastic and CBs density emerge from the different continents: Asian and Latin America beaches and seas are characterized by plastic and CBs densities higher than 1 item for square meter, with critically situations in India (2-6.5 items/ m^2), Indonesia (92 items/m^2), Sri Lanka (4 items/ m^2) and Colombia (4.5 items/ m^2), while European, North American and Australian costs and seas are less polluted with a plastic and CBs density lower than 1 items/ m^2 (Howlader et al., 2024b; Thuan et al., 2024).

The environmental impact of this pollution is significant, as CBs are composed primarily of CA, a type of plastic that does not readily biodegrade. This leads to long-term contamination of ecosystems, particularly marine environments, where the butts can leach toxic substances and contribute to microplastic pollution. Efforts to mitigate this issue include public education campaigns, the provision of proper disposal facilities, and initiatives aimed at reducing smoking rates. However, CBs remain a significant environmental pollutant, necessitating ongoing attention and action to address their production and dispersion.

The advent of electronic cigarettes (e-cigarettes) has introduced new dynamics in tobacco consumption and its environmental impact. They, particularly reusable models, do not produce CBs, potentially reducing this specific form of litter. However, the rise of disposable e-cigarettes has introduced new environmental challenges. These single-use devices contribute to electronic waste, as they contain plastics, batteries, and hazardous chemicals. It is reported that 1.3 million disposable vapes are

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Abbreviations: CA, Cellulose acetate; CBs, Cigarette Butts; C&I, Construction and Infrastructure; CNF, Cellulose nanofibers; COD, Chemical Oxygen Demand; DES, Deep Eutectic Solvents; DS, Degree of Substitution; EC, Electrocoagulation; PAE, Pectin Acetylesterase; PAHs, Polycyclic Aromatic Hydrocarbons; TRL, Technology Readiness Level; UHI, Urban Heat Island.

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discarded weekly, contributing to electronic waste and environmental pollution (Financial Times, 2024). Improper management of disposable vapes can lead to environmental contamination, including the release of heavy metals and nicotine into ecosystems (Wang et al., 2016). In summary, while reusable e-cigarettes may reduce the number of traditional CBs, the proliferation of disposable e-cigarettes has introduced new environmental challenges. The net effect on environmental pollution depends on consumer behavior, regulatory measures, and the adoption of proper disposal and recycling practices for both traditional and electronic smoking products.

Despite their abundance and toxicity, CBs are often improperly collected and rarely recycled into 'secondary raw materials' to produce new items. Given their chemical composition, primarily based on CA, CBs are classified as organic compounds and could potentially be valorized within a biorefinery framework by converting CA into cellulose and subsequently into simpler biological precursors. As a result, their potential is often significantly unexploited. The integration of CBs into a biorefinery loop has not yet been addressed in recent scientific literature, which has instead primarily focused on the environmental impacts of CBs or explored alternative valorization pathways (Beutel et al., 2021; Chen et al., 2025; Pazzaglia and Castellani, 2023).

This perspective paper not only provides an overview of the current conventional applications of CBs but gives novel insight for their integration in a biorefinery loop for the production of biofuels and high-value compounds. Existing experiences are discussed, along with the main challenges and limitations that currently hinder their large-scale implementation.

2. Legislation aspects

CBs littering has garnered significant legislative attention globally due to its environmental impact. In Italy, the issue is addressed under the "Codice dell'Ambiente" (Presidenza del Consiglio dei Ministri, 2006), which imposes administrative fines for improper waste disposal, including CBs. Despite these regulations, studies indicate that approximately 64% of cigarettes smoked in Italian public spaces are improperly discarded, and 40% of consumers are unaware of specific regulations against littering small waste items (Erion, 2023). To enhance compliance with single-use plastic laws, major tobacco companies in Italy have established Erion Care, a national consortium aimed at raising awareness and preventing tobacco waste littering. This initiative also contributes to the costs associated with removing, sorting, and treating such litter (Philip Morris International, 2023). The European Union has been addressing CBs pollution since May 2018 as part of the European Strategy for Plastics in a Circular Economy. This strategy includes directives to phase out unnecessary single-use plastics, targeting items like CBs, which are among the top ten types of litter found on Europe's beaches (World Health Organization, 2022).

In other Countries, various measures have been implemented to combat CBs littering. For instance, Luxembourg has proposed fines of €49 for individuals caught discarding them improperly (Luxembourg Times, 2015). Washington State imposes a penalty of $1,025 for littering cigarette filters (Freire Lima et al., 2021). The Netherlands is considering a ban on cigarette filters to address environmental concerns, with some environmental groups advocating for increased fines for littering, currently set at €150 per offense (I Am Expat, 2023). Such measures aim to deter improper disposal and encourage responsible behavior among smokers. An example is represented by the Product Design Regulations. In this framework, there is ongoing debate about banning the sale of filtered cigarettes altogether due to their environmental impact. Some researchers suggest that eliminating filters could reduce litter and the associated environmental hazards (Healton et al., 2011). But public education campaigns are probably the most effective way to reduce the releasing of CBs in the environment. In fact, raising awareness about the environmental impact of CBs is crucial as they can inform the public about the consequences of littering and promote proper disposal and participation in recycling programs.

All these legislative efforts and educational initiatives reflect a growing recognition of the environmental hazards posed by CB littering, which is caused both by the nature of CA, the main polymer constituting the CBs and by the toxic molecules adsorbed during the smoking activities.

3. Chemical nature of the CBs

The increase in legislative initiatives and actions against the uncontrolled disposal of CBs in the environment is essentially due to their chemical and physical composition which leads to the release of toxic compounds, from one hand, and to their low degradation kinetics, on the other one, which cause their accumulation both in soil and water ecosystems (Shaibur et al., 2024).

CBs can be defined as the residual remnants of cigarettes after smoking, primarily composed of a filter and any remaining tobacco. The filter is mainly made of CA, a type of bioplastic derived from cellulose (Table 1). This material is chosen for its ability to trap particulate matter and some gases from smoke, aiming to reduce the inhalation of harmful substances (Farzadkia et al., 2022). However, CA is not readily biodegradable and can persist in the environment for long periods, contributing to pollution. In addition to the filter, CBs contain remnants of tobacco and ash, which harbor a variety of toxic substances (Table 1) (Marinello et al., 2020). These include nicotine, heavy metals like mercury, cadmium and lead (Dobaradaran et al., 2018), and various carcinogenic compounds formed during the combustion process (Dobaradaran et al., 2020). When discarded improperly, these toxicants can leach into the environment, posing risks to soil and aquatic ecosystems (Battista et al., 2023).

Understanding the composition of CBs is crucial for developing effective waste management strategies and mitigating their environmental impact.

As anticipated, the majority of cigarette filters are mainly made of CA, the acetate ester of cellulose coming from the reaction of cellulose with acetic acid (Haske-Cornelius et al., 2017a). This polymer is a very recalcitrant material that needs a deacetylation step to accelerate the kinetics of its biodegradation (Moroz et al., 2021). Bonanomi et al., (2020) demonstrated that both short and long term degradation of untreated CBs was not efficient. In particular, they performed extensive research on CBs at different environmental conditions (laboratory and open field) to evaluate mass loss and CBs carbon quality alteration at different time intervals. They reported that CBs decomposition involves three stages: an initial fast decay of 15% - 20% mass loss in the first 30 days, attributed to the degradation of the external involving tipping paper; then a slow 2-year decomposition period which accounts for approximately 10% mass loss and is rather independent of surrounding

Table 1
Chemical nature of CBs and their impact on the environment (Battista et al., 2023; Slaughter et al., 2011a).

Component	Description	Environmental Impact
CA	A bioplastic derived from cellulose, used in the filter to trap particulate matter.	Non-biodegradable; persists in the environment for years, contributing to litter and potential ingestion by wildlife.
Tobacco Residue	Remnants of unburned tobacco containing nicotine and other chemicals.	Contains toxic substances that can leach into soil and water, harming organisms.
Ash	Combustion by-products consisting of inorganic minerals.	May contain trace amounts of heavy metals; it contributes to soil and water contamination.
Chemical Additives	Various substances added during manufacturing, including flavorings and humectants.	Some additives can be toxic to environmental organisms; potential for bioaccumulation.

Abbreviations: CA, Cellulose acetate; CBs, Cigarette Butts conditions; and finally the last stage where environmental conditions affect decomposition rate significantly.

As a consequence of the low degradation kinetics, CBs can leach into the environment the numerous toxic compounds accumulated during smoke. Among them, nicotine, heavy metals and PAHs are the most abundant ones (Wright et al., 2015). Nicotine is a potent alkaloid present in tobacco, which is retained in the filter and residual tobacco of CBs. Studies have shown that a single CBs can release nicotine into water at concentrations exceeding the "Predicted No Effect Concentration" of 2.4 μg/L, potentially harming aquatic organisms (Moriwaki et al., 2009). Moreover, CBs contain various heavy metals absorbed from tobacco during smoking. Research indicates the following average concentrations in freshly smoked CBs: Chromium (Cr): 1.77 μg/g, Nickel (Ni): 2.88 μg/g, Copper (Cu): 12.93 μg/g, Zinc (Zn): 24.25 μg/g and Lead (Pb): 1.77 μg/g (Darabi et al., 2023). These metals can leach into the environment, with their emission increasing by 8–10% as CBs remain in the environment over time. Rainfall can further accelerate this leaching process, increasing metal emissions by 18–20% (Faisal et al., 2024). Beyond heavy metals, PAHs are other toxic compounds present in CBs. They are formed during the incomplete combustion of organic material and are associated with the increasing risk of developing cancer. CBs have been found to contain various PAHs, which can leach into the environment, posing risks to both terrestrial and aquatic life. Finally, other compounds, such as ethylphenol, are present in these wastes and contribute to their overall toxicity, especially of aquatic ecosystems (Torkashvand et al., 2020), affecting the life of polychaetaes, mollusks and fishes (Freire Lima et al., 2021). CBs can also kill terrestrial animals, as larvas, insects and even higher animals (mammals, birds, reptils) when they ingest CBs. Finally, different studies showed that the adverse consequences of the CBs littering are higher when they have residual tobacco, while a lower environmental impact derives from unsmoked cigarettes or smoked cigarette without residual tobacco (Slaughter et al., 2011b).

Although the great amount of CBs dispersed in the environment and the severe problems for aquatic and terrestrial ecosystems, there are not specified protocols or practises for a correct management of CBs and neither for their valorization in a circular economy optic (Freire Lima et al., 2021). In the case they are recollected, CBs are mostly landfilled and incinerated (Tataranni et al., 2021).

This review paper analysed the current options of CBs management, with a particular focus on the possibility to implement them in a biorefinery approach in the attempt to create a circular economy model designed on this specific toxic and diffused waste.

4. The most conventional CBs application field: construction and infrastructure

Although their toxicity, different studies and actions were implemented to promote CBs recycling and reuse as secondary raw materials for the production of new products. CBs found application mainly in the C&I sector, but innovative recent research works tried to valorize them for other purposes, such as in energy and the production of valuable compounds and products.

Most CB recycling methods result in the production of solid materials for C&I sector, such as fired bricks, asphalt for roads, precast concrete paving, and acoustic insulation materials. In some cases, the use of CBs revealed the potential for reducing material usage and energy consumption during the transportation of construction materials. Additionally, for the specific case of CBs inclusion into asphalt, thermal conductivity tests showed greater resistance to damage caused by temperature fluctuations (Rahman and Mohajerani, 2021a).

More recently, CBs have also been used to manufacture environmentally friendly ceramic tiles. Specifically, this study examines the use of CBs as a partial substitute (up to 5 wt.%) for natural materials in industrial roofing tiles. The tiles were pressed, sintered at 1100°C, and evaluated for key properties such as shrinkage, density, weight loss, water absorption, and strength. Microstructural analysis confirmed the feasibility of this approach. Results suggest that CBs can be effectively incorporated into eco-friendly ceramic roofing tiles, offering a sustainable alternative for waste repurposing in construction (Maciel et al., 2020). Additionally, other independent studies have shown that the leaching of contaminants from encapsulated CBs used in construction materials is negligible (Mohajerani et al., 2022). Moreover, a new chemical treatment has been identified to clean discarded CBs before repurposing them as acoustic materials. It consists in a purification process adopting a mixture of water and ethanol to remove metal ions and pollutants, improving both the samples' appearance and acoustic performance. After cleaning and drying, the samples maintained high absorption coefficients at medium and high frequencies, making them suitable as acoustic absorbers (Gómez Escobar et al., 2021).

In the last years, CBs found an innovative application in specific C&I materials with the aim of mitigating the UHI phenomenon. UHI is defined as the accumulation of heat in urban areas due to construction and human activities, which leads to the augmentation of land surface temperatures. The main consequences of this phenomenon include changes in local climate, hydrology, soil properties, air quality, biological habits, material cycles and public health (Yang et al., 2016). Traditional construction materials, such as concrete and asphalt, contribute to this phenomenon due to their high thermal mass and ability to absorb and retain heat. Innovative researches (Ahlawat et al., 2022; Rahman and Mohajerani, 2021b) have investigated the incorporation of processed CBs into construction materials as a strategy to mitigate the UHI effect while reducing cigarette waste. In this approach, collected CBs are cleaned, dried, and encapsulated with materials like bitumen and paraffin wax to prevent the leaching of toxic substances. The encapsulated butts are then mixed into concrete at varying proportions. The inclusion of CBs introduces air voids into the concrete matrix, resulting in reduced density and thermal conductivity (Rahman and Mohajerani, 2021b). This modification decreases the heat storage capacity of the concrete, thereby contributing to lower surface temperatures in urban environments. Mechanical testing of the modified concrete indicated a decrease in compressive strength with increasing CBs content. However, the strength remained within acceptable limits for certain applications, such as pedestrian pathways and low-load-bearing structures. Additionally, the research explored the use of these wastes in asphalt concrete. Their incorporation into asphalt mixtures, led to lower thermal conductivity and improved resistance to deformation under load. These properties are advantageous for pavement applications, potentially leading to cooler surface temperatures and extended pavement lifespan.

5. CBs preparation in the optic of their exploitation in a biorefinery and circular economy context

5.1. Deacetylation of CA as pretreatment for CBs potential implementation in a biorefinery context

Beyond the most conventional applications in C&I sector, the usage of CBs was also studied for energy production and for the synthesis of innovative materials. These application fields require often specific pretreatment of CBs in order to remove contaminants and favor the reduction of their recalcitrant chemical nature, caused by the CA. These steps become fundamental especially when CBs exploitation involves biological processes, where microorganisms are usually not able to degrade and transform complex organic substances. Consequentially, this step is fundamental to facilitate the CA conversion into cellulose and its reuse in new products (Benavente et al., 2019).

Deacetylation of CA involves the cleavage of ester bonds, resulting in the release of acetic acid and the regeneration of hydroxyl groups on the cellulose backbone. This process can occur through chemical hydrolysis, enzymatic or physical action (De Fenzo et al., 2020a). Chemical hydrolysis involves the reaction of water molecules with the ester bonds in

CA, leading to the formation of acetic acid and free hydroxyl groups (Tulos et al., 2019). The most chemical deacetylation method is represented by the adoption of alkaline solutions, such as sodium hydroxide (NaOH), which facilitates the cleavage of ester bonds. The reaction conditions, including NaOH concentration, temperature, and duration, are critical parameters that determine the efficiency of deacetylation (Wang and Fan, 2023).

Among physical methods, ultrasonication seemed the most effective one. It can increase the reaction rate by promoting the penetration of the alkaline solution into the CA matrix and facilitating the removal of acetyl groups. For example, one study reported a rapid method for deacetylating CA nanofibers using ultrasonic energy in conjunction with NaOH/ethanol solutions, achieving significant deacetylation within a short time frame (Ahmed et al., 2017a). Remaining in the field of physical deacetylation, an innovative approach involves the use of autoclaves to facilitate rapid deacetylation. Research has demonstrated that autoclave-assisted deacetylation can effectively convert CA from CBs into cellulose within a short duration. This method offers a rapid and efficient alternative to traditional chemical hydrolysis (Putri, n.d.).

Another alternative to chemicals can be represented by the adoption of enzymes. They were able to offer a mild and environmentally friendly approach to deacetylation. Research has identified specific enzymes capable of deacetylating CA, thereby enhancing its biodegradability. For instance, PAE has been shown to effectively deacetylate CA, making it more amenable to subsequent enzymatic degradation by cellulases (Haske-Cornelius et al., 2017b). More recently, CA biodegradation was demonstrated by embedding lipase from *Candida rugosa* into CA films. After 40 days with external enzymes, CA with 5% immobilized lipase showed 88% molecular weight reduction, compared to 48% for untreated CA, due to significant deacetylation (Kalita and Hakkarainen, 2023). Esterase can also be used for deacetylation mechanism. This type of enzymes can catalyze the removal of acetyl groups from CA. Enzymes, such as PAE have been studied for their ability to deacetylate CA, facilitating subsequent degradation by cellulases (Haske-Cornelius et al., 2017c).

Whatever the pretreatment is, the efficiency of CA deacetylation is affected by several factors. The most impacting is represented by the DS. This term is referred to the average number of acetyl groups attached to anhydroglucose unit in the cellulose chain. A higher DS implies more acetyl groups, which can hinder enzymatic access and reduce the rate of deacetylation. Studies have shown that CA with a lower DS is more susceptible to enzymatic degradation (de Freitas et al., 2017; Haske-Cornelius et al., 2017c). The pH, temperature, the presence of salts or metal ions can significantly impact the deacetylation process too. For instance, certain metal ions, such as cobalt and nickel, have been found to accelerate the deacetylation of CA in buffered solutions (Murphy Andrew P, 1991). Finally, also the morphology of CA was an important factor affecting the deacetylation. It was demonstrated that nanofibrous forms, due to their high surface area, may undergo deacetylation more readily than bulk materials (Ahmed et al., 2017b; De Fenzo et al., 2020b).

5.2. *Removing contaminants from CBs*

As reported, CBs is not an easy convertible waste, not only for its chemical recalcitrant nature, characterized by the CA presence, but also for the toxic compounds which are adsorbed in the polymeric matrix during smoking and can be released in the environment, if CBs are not properly disposed (Ajibade, 2023). In a potential valorization of these materials within a biorefinery loop, including biological processes, toxic molecules can inhibit the involved microorganisms reducing the processes' yields. Consequentially, their removal can be recommended before using them for specific biorefinery processes.

In the last years, different research works were carried out to test the removal performance of toxic molecules from CBs leachate. The most conventional ones are represented by the adsorption on modified biochar, membrane filtration and chemical precipitation.

Biochar, a carbon-rich product derived from biomass, can be engineered to enhance its adsorption properties for heavy metals. Studies have shown that biochar, modified like with sulfur or iron oxides, exhibit increased affinity for heavy metals, effectively reducing their concentrations in leachate (Torkashvand et al., 2021). Advanced membrane technologies, including nanofiltration and reverse osmosis, have been employed to separate heavy metals from contaminated water, such as CBs leachate. These membranes act as barriers, allowing water molecules to pass while retaining heavy metal ions (Farzadkia et al., 2024a). Chemical precipitation is another very common techniques for the purification of contaminated liquid effluents. It leads heavy metals to form insoluble precipitates that can be separated from the water. Agents such as lime or sulfide compounds are commonly used to induce precipitation of heavy metals like lead and cadmium (Farzadkia et al., 2024a).

A more innovative method to desorb toxic molecules from the CBs matrix EC (Farzadkia et al., 2024b). Using aluminum electrodes, the study tested various operational parameters, including current density, reaction time, and pH levels, to optimize removal efficiency. The results demonstrated that heavy metal removal was highly effective, with efficiencies exceeding 90% for nickel, chromium, cadmium, and lead under optimal conditions. This high efficiency was attributed to the formation of aluminum hydroxide flocs, which facilitated the adsorption and precipitation of heavy metals. Moreover, organic pollutant reduction was detected by the changing of the COD and turbidity, which are indicators of organic and particulate contamination. COD was reduced by 47.1%, while turbidity decreased by 41.2%. Although these reductions were significant, they were lower than those observed for heavy metals, suggesting that additional treatment processes might be necessary to achieve complete purification. The researchers noted that the efficiency of EC was significantly influenced by pH levels, with an optimal range between 6.5 and 8.0. Additionally, the introduction of sodium chloride as a supporting electrolyte improved conductivity and enhanced pollutant removal rates.

Phytoremediation is a more innovative approach for the purification of CBs. It utilizes plants to absorb, concentrate, and precipitate heavy metals from contaminated environments. For instance, the Chinese Brake fern (*Pteris vittata*) has been identified as an effective hyperaccumulator of arsenic, while *Thlaspi caerulescens* is known for accumulating cadmium and zinc. These plants can extract heavy metals from soil or water and from CBs, storing them in harvestable plant parts, thereby reducing environmental contamination (Barasarathi et al., 2022).

Next to the discussed conventional methods, other strategies both for the deacetylation and for the purification of CBs from contaminants and toxic compounds have been reported in Table 2.

6. CBs revamping in a biorefinery and circular economy context

As discussed, deacetylation of CA can be considered a pretreatment for the implementation of a biorefinery centered on the valorization of CBs. Deacetylation can lead to improve biodegradation of the CBs, thereby reducing environmental pollution. Moreover, the regenerated cellulose has potential applications in the bioenergy field or to obtain new products with specific properties able to revamp a toxic waste, such as CB, into a high added value compounds or fuels.

Some examples of fuels and new products production from CBs have been reported along this paragraph. A brief summary of the main concepts regulating the different technologies tested on CBs is available in Table 3.

6.1. *Bioethanol Production from CBs*

One of the most recent and groundbreaking applications of CBs in biorefinery is the production of bioethanol by Battista et al. (2023). The

Table 2
Strategies for deacetylation and detoxification of CBs: a comparative analysis.

Method	Description	Advantages	Disadvantages
Alkaline Hydrolysis	Treatment with aqueous NaOH or KOH solutions to remove acetyl groups.	Effective deacetylation; enhances enzymatic digestibility; scalable process.	Requires neutralization; potential environmental impact due to chemical use.
Organosolv Process	Use of organic solvents (e.g., ethanol) with alkaline catalysts to deacetylate CA.	Efficient removal of acetyl groups; potential for solvent recovery and reuse.	Solvent recovery systems needed; potential flammability and toxicity concerns.
DES	Application of DES (e.g., choline chloride-based) for deacetylation.	Green solvents; biodegradable; tunable properties.	Limited industrial-scale data; potential cost implications.
Thermal Alkaline Pretreatment	Heating CBs with alkaline solutions at elevated temperatures (e.g., 30–121°C).	Enhances biodegradability; reduces acetyl content significantly.	Energy-intensive; equipment corrosion risks.
Enzymatic Deacetylation	Use of enzymes like acetylesterase and endoglucanase to remove acetyl groups.	Specific action; operates under mild conditions; environmentally friendly.	Slower reaction rates; enzyme cost and stability issues.
Solvent Washing (e.g., Methanol-Acetone Mix)	Sequential washing with solvents to extract contaminants.	Effective removal of organic pollutants; improves purity of recovered CA	Solvent disposal and recovery challenges; potential health and safety concerns.
Hot Water and Ethanol Washing	Washing CBs with hot water and ethanol to remove soluble contaminants.	Simple and low-cost; reduces toxicity; enhances material quality.	

Abbreviations: CA, Cellulose acetate; CBs, Cigarette Butts; DES, Deep Eutectic Solvents

Table 3
Valorization Strategies for CBs: Technologies, Products, Strengths and Challenges.

Technology	Final Product	Advantages	Challenges
Deacetylation + Enzymatic Hydrolysis	Fermentable sugars, bioethanol	High-value biobased product, renewable energy	Cost of enzymes/ chemicals, scalability limitations
Pyrolysis	Biochar, bio-oil, syngas	Versatile outputs, established process	High temperatures required, handling of toxic byproducts
Upcycling in Construction	Bricks, asphalt, ceramics	Waste reduction, improved material performance	Risk of pollutant leaching if not properly encapsulated
Supercapacitors / Electrocatalysis	High-performance functional materials	Innovative, high-added value	Early-stage technology, requires thorough decontamination
CNF Production	Reinforcement agents for composites		

Abbreviations: CNF, Cellulose nanofibers

process involved different steps and started with the removal of the acetate groups from the CA found in CBs. The deacetylation step is crucial, as the presence of acetyl groups inhibits the enzymatic hydrolysis of cellulose. The authors have tested different chemical and biological pretreatments to remove CA from cellulose, finding that lipase enzymes were the best ones to catalyze the deacetylation reaction, making the cellulose more amenable to subsequent processing. Following deacetylation, enzymatic hydrolysis was performed using cellulases, which broke down the cellulose into fermentable sugars such as glucose. The enzymatic activity was carefully optimized to ensure maximum sugar yield, while reducing the amount of high cost cellulase. Once the hydrolysis step was complete, the resulting sugars solution, especially glucose, was subjected to fermentation. Various yeast strains, including *Saccharomyces cerevisiae*, were adopted to convert the sugars into bioethanol under controlled conditions of temperature (35°C) and neutral pH. This study demonstrated that the yield of bioethanol from CBs was comparable to that obtained from traditional lignocellulosic biomass, making this an attractive alternative for biofuel production. Anyway, different challenges remain: this biorefinery involves more steps and high costing enzymes which could prevent the economic feasibility of the process and, consequently, its scale-up from laboratory to pilot TRL.

6.2. Pyrolysis of CBs for valuable chemicals and fuels

Pyrolysis, is a very well-known thermochemical decomposition process which happens under anaerobic or oxygen-limited conditions releasing green biothermal energy and bioactive chemicals, including biochar, bio-oils and gases (Lin et al., 2025). This process was also performed for the conversion of CBs.

The biochar obtained from pyrolysis serves as a potential soil amendment or adsorbent material, while the bio-oil fraction can be further processed into renewable fuels, such as biodiesel (Yousef et al., 2023). Specifically, Yousef et al., (2023) tested a promising strategy to improve biodiesel's combustion by the addition of triacetin as an oxygen-rich additive, which can be largely found in CBs. Pyrolysis experiments were conducted using a 200 g batch reactor at temperatures of 650, 700, and 750°C to identify optimal conditions for maximizing triacetin yield. The yield of pyrolysis products remained consistent across temperatures: about 38–39.5% oil, 25.7–27.7% char, and 33–36.4% gas. The highest triacetin content (43%) in the pyrolysis oil was achieved at 750°C. The gaseous products at this temperature primarily included CO_2 (11.6%), CO (8%), H_2 (4.6%), and CH_4 (2%). The resulting char showed a porous microstructure rich in calcium (up to 32%), with different forms appearing depending on the temperature (debris at 650°C, flakes at 750°C).

Another interesting study was more focused on biochar production by pyro-reforming of CBs (Guo et al., 2025). The process was conducted using a nickel-loaded char catalyst (Ni/char), where the char served as the support material. Experiments were performed across a temperature range of 500 to 700°C. The findings revealed that 700°C was the most effective temperature, enabling the transformation of both light organic compounds and some heavier, humic-acid-like substances into gas, with a high gas yield of 75%. At this temperature, coke formation was minimal (14%), significantly lower than the levels observed at 600°C (58%) and 500°C (32%). The higher coke formation at 600°C was attributed to the slower gasification rate compared to cracking, leading to the buildup of carbon-rich intermediates. While the reforming process began at 500°C, most organic components in the resulting bio-oil were not effectively converted at this lower temperature. The coke produced was more aromatic than the original biochar, and its aromaticity increased with temperature, which removed oxygen-containing groups and made the used catalyst more hydrophobic. Structural analysis showed that nanofiber-like features formed on the Ni/char catalysts at 500 and 600°C, whereas at 700°C, the material predominantly consisted of carbon nanotubes. This difference was due to the higher presence of oxygenated compounds and fewer hydrocarbon intermediates at lower temperatures. Lastly, the presence of nickel enhanced the combustibility of the spent catalyst, and nickel could be recovered as NiO for potential reuse in fresh catalyst preparation.

Other strategies were tested to obtain activated carbon from CB. The processes started with pyrolysis, to form a porous carbon structure, which serves as a precursor for activated carbon production. To enhance the adsorption properties of the material, chemical activation is performed. This involves the treating of carbonized CBs with activating agents such as potassium hydroxide (KOH) or sodium hydroxide (NaOH). These chemicals create a well-developed porous network by etching the carbon surface, thereby increasing its surface area and adsorption capacity. Supercritical CO_2 extraction is sometimes employed to further refine the material, removing residual impurities and enhancing its performance. Characterization studies confirm the highly porous nature of the produced activated carbon, making it suitable for applications such as water purification and gas adsorption (Burdese, 2021; Herrera-Puerta et al., 2025) .

Finally, another study tested the pyrolysis on e-cigarettes filters to obtain biochars, biofuels, activated carbons and other compounds. These include acetic acid, phenols, and hydrocarbons, which have significant industrial applications (Czégény et al., 2021). It demonstrated the transferability of pyrolysis also on the new smoking products on the markets.

6.3. *Other groundbreaking technologies for the valorization of CBs*

Beyond the most consolidated biorefinery technologies, such deacetylation, sugars fermentation or pyrolysis, some innovative approaches were performed for the obtaining of new products from CBs able to represent a valid alternative to expansive materials from conventional fossil fuels. Recent studies have explored the CBs transformation into: i) eco-friendly, platinum-free electrocatalysts for fuel cells, ii) high-performance supercapacitor materials and iii) the upcycling of their filters into cellulose nanofibers, and their incorporation into construction materials to mitigate UHI effects.

6.3.1. *Platinum free catalyst from CBs*

The innovative research by Testa et al., (2023) focused on an innovative and sustainable way to recycle CBs were first carbonized in a nitrogen atmosphere to create a carbon-rich base material. Then, the research team introduced metals like iron, cobalt, or nickel into the structure which are crucial for promoting oxygen reduction reactions in various environments—acidic, neutral, and alkaline. Surprisingly, the performance of these low-cost, waste-derived catalysts was comparable to that of commercial platinum-based catalysts, especially in alkaline conditions. The takeaway of the research is quite impactful: not only can CBs be transformed from waste into useful, high-performing materials, but they also offer a green and economical alternative to expensive platinum catalysts in fuel cell technologies.

6.3.2. *Conversion of CBs into High-Performance Supercapacitor Materials*

CBs were also explored in energy storage applications, particularly in the development of supercapacitors. Supercapacitors are energy storage devices known for their rapid charge and discharge capabilities, high power density, and long cycle life, making them essential components in modern electronics, electric vehicles, and renewable energy systems. A pivotal study conducted by a team of South Korean scientists (Lee et al., 2014) demonstrated a method to convert used cigarette filters into a carbon-based material suitable for supercapacitor electrodes. The process involved a one-step pyrolysis technique, where the CA fibers in the filters are subjected to high temperatures in the presence of nitrogen gas. This thermal decomposition results in the formation of porous carbon structures with a high surface area, which exhibited remarkable electrochemical properties. Tests revealed a specific capacitance of approximately 243 F/g, surpassing the performance of many commercially available carbon materials, including activated carbon, graphene, and carbon nanotubes. This high capacitance is attributed to the unique porous structure and substantial surface area of the carbon derived, which facilitate efficient ion transport and storage.

6.3.3. *Upcycling Cigarette Filters into High-Performance Cellulose Nanofibers*

Recognizing the potential of CA in CBs, some researchers have explored methods to upcycle used cigarette filters into CNF, which have applications across various fields due to their exceptional mechanical properties and biodegradability. A study detailed a multi-step process to extract and convert CA from discarded cigarette filters into regenerated cellulose nanofibers (Fathi et al., 2024). The process begins with the collection and cleaning of used filters to remove residual tobacco and contaminants. The cleaned filters undergo a deacetylation process, typically involving alkaline treatment, to convert CA into pure cellulose. Subsequently, cellulose is subjected to mechanical fibrillation techniques, such as high-shear homogenization or electrospinning, to produce nanofibers with diameters ranging from 10 to 100 nanometers. The resulting cellulose nanofibers exhibited high crystallinity and tensile strength, making them suitable for reinforcing composite materials, filtration membranes, and biomedical applications. Additionally, their high surface area and hydrophilicity render them effective as emulsifying agents in food and cosmetic industries.

This upcycling approach offers a sustainable source of high-value cellulose nanofibers, reducing reliance on virgin materials and contributing to resource efficiency. The study also explored the application of the derived CNF in stabilizing oil-in-water emulsions, demonstrating their effectiveness in forming stable emulsions without the need for synthetic surfactants. This finding suggests potential applications in the formulation of environmentally friendly emulsions in various industries.

6.4. *Comparative overview of CBs valorization approaches*

To facilitate a comprehensive understanding of the valorization potential of CBs through various biorefinery pathways, Table 3 summarizes the main options and the final products from the valorization of CBs discussed along the review, while Table 4 focuses on the key findings from the biorefinery solutions, discussed in Sections 6.1 to 6.3. The summarized data cover representative studies on bioethanol production, thermochemical conversion, and transformation into advanced materials. Each route is characterized by specific pre-treatment requirements, reaction conditions, and target products, with performance indicators such as yields, surface area, or energy outputs included when available. Despite the promising results at laboratory scale, comparability among the different studies remains limited due to variations in CBs origin, pretreatment protocols, and process parameters. Moreover, only a few studies report techno-economic or life-cycle data, making it difficult to assess the overall sustainability and scalability of the proposed technologies. Nevertheless, this comparative overview highlights the versatility of CBs as a feedstock and underscores the importance of integrated approaches combining material recovery, energy generation, and pollutant mitigation. Future efforts should aim to harmonize experimental protocols and prioritize environmentally sound and cost-effective pathways to facilitate the transition from proof-of-concept to industrial implementation.

7. Projects and programs for the revamping of CBs

In response to the environmental challenges posed by CBs, several organizations have developed innovative recycling programs aimed at repurposing this waste into useful products. All these initiatives promote the awareness of citizens of the potential negative effects of the CBs when are not properly collected and managed, as consequence of their low degradability and toxicity, offering some alternative for their recycling and revamping into new objects at the same time. By this way, CBs can enter in the virtuous model of the circular economy, preventing the exploitation of virgin new materials.

In the next lines some examples of recent and innovative startups and projects have been presented.

Table 4
Summary of experimental pathways for the valorization of CBs within a biorefinery framework.

Valorization Route	Pretreatment	Key Conditions	Product(s)	Yield / Output
Bioethanol	Deacetylation + Enzymatic Hydrolysis	NaOH or lipase deacetylation; 35°C, neutral pH fermentation	Fermentable sugars, bioethanol	Comparable to lignocellulosic biomass
Pyrolysis (bio-oil, biochar)	Drying	650–750°C in 200 g batch reactor	Bio-oil, biochar, gas	Oil: 38–39.5%; Char: 25.7–27.7%; Gas: 33–36.4%
Pyro-reforming	Drying	500–700°C with Ni/char catalyst	Synthesis gas, carbon nanotubes	Gas yield up to 75%
Activated carbon	Pyrolysis + chemical activation	KOH or NaOH treatment; optional CO_2 extraction	Activated carbon	High surface area
Platinum-free catalyst	Carbonization + metal doping	N_2 atmosphere + Fe, Co, Ni doping	Metal-N-C electrocatalyst	Performance comparable to Pt catalysts
Supercapacitor material	Pyrolysis	One-step pyrolysis in N_2	Porous carbon	Capacitance ~243 F/g
Cellulose nanofibers	Cleaning + Deacetylation + Fibrillation	NaOH treatment + homogenization/ electrospinning	Cellulose nanofibers	Diameter 10–100 nm; high crystallinity

7.1. *TerraCycle's Cigarette Waste Recycling Program (TerraCycle, 2023)*

TerraCycle is an innovative recycling company based in the USA. The project accepts extinguished cigarettes, cigarette filters, loose tobacco pouches, outer plastic packaging, inner foil packaging, rolling paper, and ash. Participants can collect these materials and ship them to TerraCycle for recycling. The service is free, though participants must provide their own containers. The recycling process involves different unit operations. At the recycling facility, the CBs are first sorted into their main components: residual tobacco and ash, paper, and plastic filters. The organic material is processed through industrial composting, as it is biodegradable and contributes to the creation of nutrient-rich compost. The paper is also composted, when possible, though in cases of heavy contamination, it may be discarded. The remaining CBs are treated through a combination of mechanical and chemical processes to transform them into plastic pellets, which can be used in the manufacturing of various durable products, such as park benches, ashtrays, shipping pallets, and other items, effectively giving a second life to what would otherwise be a persistent pollutant. By implementing this closed-loop recycling model, TerraCycle not only diverts millions of CBs from landfills and natural environments, but also raises public awareness about the environmental impact of cigarette litter.

7.2. *Keenat's Recycling Efforts (Keenat, 2022)*

Keenat, founded in 2018 and operating throughout France, focuses on the recycling of CBs by extracting the plastic contained in the filter (CA) and mixing it with other recycled plastics to create a new recyclable plastic polymer. The process begins with the collection of cigarette waste using specially designed ashtrays, which are placed in various public and private areas. Because CBs are considered hazardous waste, due to the presence of toxic substances like nicotine and heavy metal, Keenat follows strict regulations for their traceability and handling. Once transported to Keenat's dedicated recycling facility near Bordeaux, the CBs undergo a decontamination process that is both innovative and sustainable. Unlike many industrial processes, Keenat's method does not use water or chemical solvents, which helps conserve resources and avoids secondary pollution. The waste is instead treated through successive heating cycles, reaching temperatures close to 200°C. This thermal treatment effectively eliminates harmful substances such as nicotine, phenol, and pesticides, rendering the material non-toxic. Following decontamination, the CA found in CBs is recovered and blended with other recycled plastics to produce a new, recyclable polymer. This material is then transformed into useful products, primarily educational and awareness signage installed in public spaces like parks, universities, and municipal buildings. These products serve not only a functional role but also a symbolic one, acting as tools to raise awareness about the environmental impact of cigarette litter and to encourage more responsible behavior. In parallel, Keenat continues to invest in research and development to further refine its processes. Current investigations include the use of supercritical CO_2 for improved deodorization of the recycled material.

7.3. *FiltraCycle's Plastic Products (FiltraCycle, 2023.)*

FiltraCycle is an innovative company based in Dublin, Ireland, dedicated to addressing the environmental challenges posed by CBs litter. The scope of FiltraCycle is represented by the turning CBs into high-quality plastic products. The company's approach begins with their collection through strategically placed receptacles known as "FiltraBins". These bins are installed in various public spaces, including college campuses, bars, and city centers, to facilitate the gathering of cigarette waste. Once collected, the butts undergo a meticulous recycling process where the CA is extracted and purified, transforming it into clean plastic pellets. These recycled pellets serve as a sustainable alternative to virgin plastic in the manufacturing of various consumer products. FiltraCycle's plastic has been utilized in the production of items such as sunglasses, demonstrating its versatility and appeal to eco-conscious brands. The company estimated that more than 360,000 CBs were already recycled and valorized by this way.

7.4. *The Re-Cig's startup Upcycling Process (Re-Cig, 2023)*

Re-Cig is an innovative Italian startup, founded in Trento in 2019 and inspired by the principles of circular economy. The project has developed a patented system for transforming CBs into virgin material that can be used to produce new objects through an upcycling process. They provide services to both private and public entities, installing ashtrays and offering cleaning, collection, and disposal services for CBs. Specifically, the CBs follow a transformation which includes different steps. The first is represented by the collection. This action is made in collaboration with various partners, including universities and public bodies, to establish collection points for CBs, often using designated "Smokers Point" ashtrays. Then, the CBs are separated from the residual tobacco and paper, while the CA filters are cleaned thoroughly. The cleaned CBs are melted and extruded, forming a plastic polymer (Re-Ca®). This material is then ground into granules for use in various applications. The Re-Cig project includes also the transformation of the Re-Ca® granules into final products by the usage of 3D printing to obtain everyday objects like umbrella handles, spectacle frames, and other products.

8. Challenges in the CBs exploitation in biorefinery processes

The previous examples of initiatives, projects, and startups demonstrate the potential for recycling CBs and transforming them into new products. While these efforts are commendable and play an important role in raising public awareness about the importance of CB recycling, they are largely limited to the purification of CBs and the melting and granulation of the CA fibers to produce new plastic materials. In some cases, these materials are also integrated into construction applications to enhance the physical properties of existing products (Sarwar et al., 2023) (Mohajerani et al., 2020).

However, the transformation of CA into cellulose and its subsequent use in the production of bio-based compounds remains confined to a handful of laboratory-scale studies. This indicates that CBs are still far from being recognized as a viable alternative green carbon source, unlike other biomass types. Several key challenges must be addressed before biorefinery applications based on CBs can reach higher TRLs.

One of the primary obstacles is the complex composition of CBs. They consist of CA fibers, residual tobacco and a variety of toxic chemicals absorbed during smoking. This complexity necessitates intricate treatment processes to isolate and neutralize toxic components. Sequential chemical treatments are required to both remove contaminants and convert CA into cellulose, which could then serve as a substrate for microbial fermentation into high-value compounds.

Economic viability also poses a significant challenge. The cost of collecting, transporting, and processing CBs is high and may exceed the economic value of the resulting recycled products. Additionally, biorefinery approaches often rely on expensive chemicals or enzymes to convert CA into cellulose or simple sugars. Thus, the development of cost-effective technologies and the establishment of markets for products derived from cigarette waste are critical for ensuring long-term sustainability. Process optimization is another essential factor. Achieving efficient deacetylation, while preserving the integrity of the cellulose, requires careful control over reaction parameters such as temperature, reaction time, and reagent concentration. Furthermore, the environmental impact of deacetylation processes must be taken into account. The use of harsh chemicals for deacetylation raises concerns about waste management and potential environmental harm, which in some cases may even outweigh the environmental burden of disposing of CBs in appropriate landfills.

Public participation plays a crucial role in the success of any recycling initiative. Encouraging smokers to dispose of their CBs properly and to engage in recycling efforts requires ongoing education campaigns and the provision of convenient disposal infrastructure. Lastly, citizens must be involved not only to assure a successful recollection of CBs but also informed about their application and the technology to convert them in new products. It is crucial to increase the social acceptance of CBs derived objects. Given the toxic nature of CBs, public skepticism may arise regarding the safety and purity of intermediate and final products derived from them, especially in the case of bio-based applications. Addressing these concerns is essential to foster trust and acceptance among consumers.

9. Conclusions and recommendations

The valorization of CBs through biorefinery strategies offers a promising avenue for transforming toxic waste into valuable products, aligning with circular economy principles. This review highlighted a variety of conversion routes, ranging from reuse in construction and energy storage to the production of bioethanol and nanomaterials, demonstrating the potential of CBs as a non-conventional feedstock. However, significant barriers remain, notably the toxic and heterogeneous nature of CBs, which requires complex pretreatments such as deacetylation. These processes are still mostly confined to laboratory settings, and their environmental and economic sustainability must be better assessed. A key novelty of this paper lies in providing a comprehensive, system-level perspective that integrates technological pathways and environmental impact dimensions, which are often addressed separately. While a few pioneering initiatives are proving the feasibility of CB recycling, widespread implementation still faces hurdles: lack of standardized protocols, low TRL and cost-effectiveness. Future research should prioritize green and scalable pre-treatment methods, alongside policy frameworks that support selective collection and valorization infrastructures. Specifically, efforts should focus on the development of low-cost, low-impact deacetylation technologies, and on promoting the adoption of CBs in existing pilot biorefineries to assess the real feasibility of full-scale implementation.

CRediT authorship contribution statement

Federico Battista: Writing – original draft, Investigation, Data curation, Conceptualization.

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.

Data availability

No data was used for the research described in the article.

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