

Closing the Loop in Vitiviniculture and Spirit Production: From Grape Processing Waste to the Multifunctional Biochar

Paraskevi Chalatsi-Diamanti, Ekavi Aikaterini Isari, Eleni Grilla, Petros Kokkinos * and Ioannis K. Kalavrouziotis

Laboratory of Sustainable Waste Management Technologies (LSWMT), School of Science and Technology, Hellenic Open University (HOU), 18 Aristotelous Str., 26335 Patras, Greece; paraskevi.chalatsi@ac.eap.gr (P.C.-D.); ekavi.isari@eap.gr (E.A.I.); egrilla@eap.gr (E.G.); ikalabro@eap.gr (I.K.K.)

* Correspondence: pkokkin@eap.gr

Abstract

Viticulture, winemaking, and distillation industries produce substantial quantities of organic by-products (grape prunings, stems, marc-pomace, spent yeast, wine lees, distillation heads and tails, stillage), presenting both environmental challenges and promising opportunities for sustainable valorization. This narrative review offers a comprehensive analysis of the viticulture, winemaking, and distillation processes, along with the characterization of their solid and liquid by-products. Furthermore, it examines the chemical composition and mentions main valorization strategies for these residues, emphasizing their potential both as feedstocks for biochar production and as sources of valuable solvents. Additionally, various applications of biochars are explored, with particular focus on biochar derived from grape pruning and grape pomace-marc biomass, highlighting its effectiveness as a sorbent for environmental contaminants. Moreover, a broad range of biochar activation and modification methods that enhance physicochemical properties and expand functional applications is reviewed. Solvent-based biochar modification is also examined in order to introduce a novel concept: employing grape distillation liquid by-products (heads and tails fractions) to activate biochars made from grape prunings and pomace, creating a high-value sorbent while simultaneously valorizing two major waste streams. This dual-use strategy offers a new pathway for circular resource management within the viticulture and winemaking sectors.

Keywords: viticulture; winemaking; distillation; biochar; modification; by-products

1. Introduction

Viticulture and the production of wine and spirits have been integral cultural, social, and economic activities throughout the Mediterranean region since antiquity [1]. Despite a modest decline in global wine consumption over recent years, global annual consumption remains high, with Europe and more particularly France, Italy, Spain, and Portugal standing out as the leading consumers. In 2024 only, 214.2 million hectoliters of wine were consumed worldwide. Similarly, the global spirits sector has shown robust growth, with consumption reaching approximately 38.1 billion liters in the same year [2,3].

However, alongside their economic and cultural importance, these industries generate significant volumes of organic by-products throughout the production chain: grape prunings, stems, marc-pomace, spent yeast, wine lees, distillation heads and tails, stillage.

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From vineyard management and grape cultivation to fermentation and distillation, each stage produces waste materials that present both environmental challenges and opportunities for sustainable valorization [4]. Managing these residues is a growing concern, particularly due to their high organic load and seasonal production. For instance, the wine-making process is estimated to produce 0.3–0.5 kg of by-products per liter of wine, in addition to the residues generated during the winter pruning season [5,6]. If not properly handled, these by-products can lead to various environmental issues such as greenhouse gas emissions, soil degradation, and water contamination. Thus, a comprehensive understanding of these processes and their associated by-products is critical in order to address these environmental challenges and to advance sustainable practices in viticulture, oenology and spirit production [7].

Among the available sustainable valorization strategies for solid waste, thermochemical conversion, and especially pyrolysis, has emerged as a highly promising approach, primarily due to the versatility of its products: biochar, bio-oil, and syngas [8]. Of these, biochar is especially notable for its stability, high surface area and carbon-rich composition, offering wide-ranging benefits in soil improvement, environmental remediation, long-term carbon sequestration, etc. [9,10]. Notably, the physicochemical properties and performance of biochar are dependent on the type of feedstock used and the specific pyrolysis conditions applied [11]. Thus, in this review, grape pomace and grape prunings (vitivinicultural waste) are considered as feedstocks for biochar production, given their abundance and favorable lignocellulosic composition. More specifically, Gabur et al. investigated grape pomace-derived biochar sorbents and reported effective removal of heavy metals and pesticides, confirming the high valorization potential of vitiviniculture residues in environmental remediation processes [12]. Similarly, Prelac et al. produced biochar from grapevine pruning residues and demonstrated its efficiency as an adsorbent for polyphenolic compounds, highlighting its potential for wastewater treatment applications [13]. Moreover, the produced biochar's functionality can be significantly enhanced through various modification techniques, which can tailor its surface area, porosity, and chemical properties. As a result, its capacity to act as an effective sorbent for environmental contaminants, such as heavy metals, nutrients, and organic pollutants, becomes more efficient [14]. Consequently, there is growing interest in optimizing biochar characteristics to meet the specific demands of these applications [15].

On the other hand, while solid waste valorization has advanced considerably, liquid by-products from winemaking and especially distillation processes remain largely underutilized, despite their richness in organic acids, phenolic compounds, and other bioactive molecules [16]. Although often discarded, distillation fractions, heads and tails cuts, contain a complex mixture of volatile and semi-volatile organic compounds, some of which may have potential as feedstocks for bio-based chemical synthesis or as low-grade industrial solvents [17]. However, their potential applications remain limited due to toxicity concerns and compositional variability, highlighting the need for further research into safe and targeted valorization strategies [18].

Therefore, this review aims to provide a comprehensive and critical assessment of the valorization of both solid and liquid by-products generated throughout the viticulture, winemaking, and distillation processes. Specifically, it addresses: (i) the composition and valorization methods of key residues, (ii) the pyrolysis conditions and feedstock influence on biochar properties, (iii) the applications of biochar, with an emphasis on its role as a sorbent for environmental contaminants and its regeneration, and lastly, (iv) biochar activation techniques. Furthermore, this review proposes a novel idea of utilizing distillation liquid by-products as activating agents for biochar produced from viticulture and wine-making residues, thereby introducing a new pathway for integrating liquid waste streams

into value-added applications. In doing so, it aims to promote a circular economy perspective in the agricultural, food and beverage sectors by demonstrating how traditionally overlooked residues can be reimagined as functional materials. An overview of this review is shown in Figure 1.

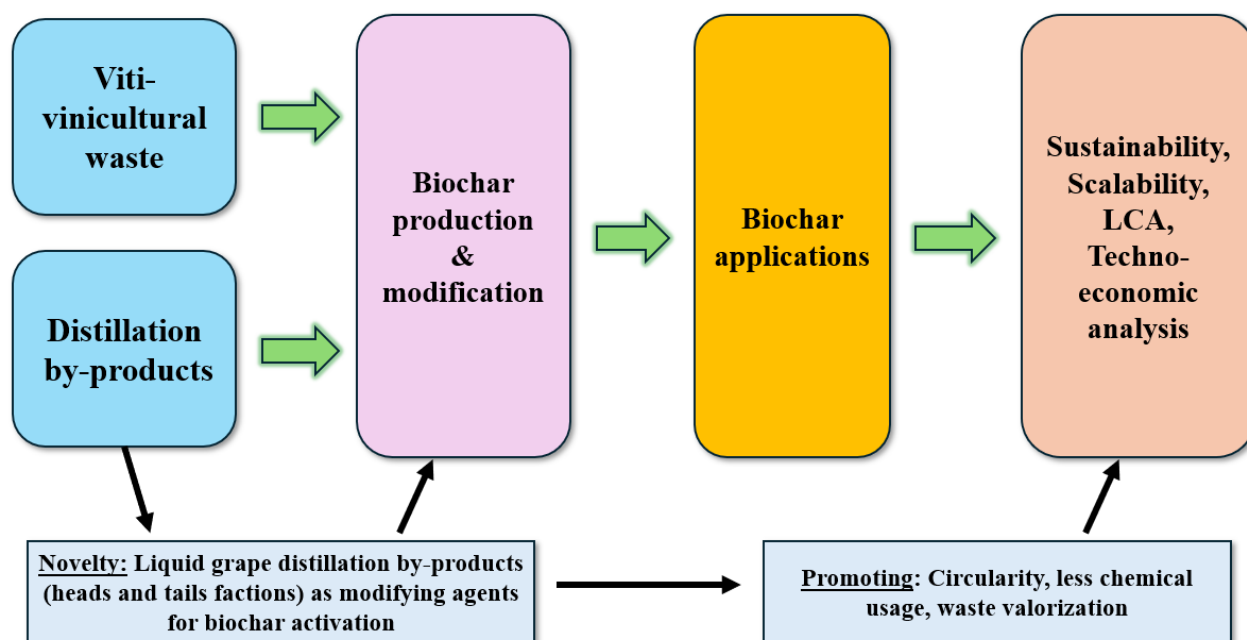


Figure 1. An overview of the main parts and novelty proposed in this review.

2. Materials and Methods

This narrative review was based on a comprehensive literature search aimed at identifying relevant publications, with particular emphasis on peer-reviewed scientific articles, published between 2010 and 2026. Searches were conducted between July 2025 and April 2026 using databases including Scopus, PubMed, and Web of Science. Keywords such as “biochar,” “biochar modification,” “vitiviniculture waste,” “distillation by-products,” and “grape processing waste” were applied to retrieve relevant studies.

Studies were considered eligible when they addressed the production, physicochemical modification, characterization, or application of biochar derived from grape-processing by-products. Both original experimental studies and critical review articles were included. Conversely, studies were excluded if they were not directly related to vitiviniculture residues, biochar production or modification, lacked sufficient experimental detail, were not peer-reviewed, or duplicated insights already covered by more comprehensive publications. Moreover, scientific relevance was assessed according to the study’s contribution to the understanding of waste valorization pathways, biochar properties, activation strategies, and potential environmental, agricultural, or industrial applications. Methodological rigor was evaluated based on the clarity of experimental design, adequacy of analytical characterization, reproducibility of methods, and robustness of the reported results. Additional references were identified through backward citation tracking of key articles and review papers. Finally, the initial search yielded 395 articles.

The final selection comprised 147 references, chosen on the basis of scientific relevance, methodological rigor, citation impact, and contribution to the thematic scope of the review. The selected literature encompassed experimental investigations, critical reviews and techno-economic evaluations, relevant to the valorization of vitivinicultural waste streams through various strategies with emphasis on biochar technologies. Finally, the

screening of records, removal of duplicates, and final selection of references were conducted manually without the use of automated systematic review software or dedicated reference management tools.

3. Results

3.1. Viticulture and Winemaking: Waste Streams, Environmental Impact and By-Product Valorization

3.1.1. Viticulture

The cultivation of grapevines, also known as viticulture, produces several categories of agricultural waste. One of the most prominent is pruning residue, composed of woody materials such as shoots, canes, and leaves [6]. These residues are generated twice annually, once during the dormant season in winter to shape and remove old wood, and again in summer to thin shoots and clusters for improved fruit quality. Consequently, there is an urgent need to effectively valorize them in order to fully realize their potential. Chemically, they are composed primarily of cellulose (30.3%), hemicelluloses (13.9–24.5%), and Klason lignin (4.6–47.3%), with notable levels of soluble carbohydrates (5.1–12.4%), dietary fibers (1.0–77.2%), lipids (0.9–3.4%) and minor amounts of nitrogen, potassium, proteins, extractives, and ash [7]. Moreover, their extractives include bioactive compounds such as proanthocyanidins, stilbenes, and flavan-3-ols, which have demonstrated antioxidant properties and potential applications in winemaking and material science [7]. The relatively wide ranges observed for several components reflect natural variability associated with grape variety, geographical origin, agronomic and seasonal conditions, as well as differences in sampling fractions (e.g., pruning vs. harvest residues) and analytical methodologies applied across studies [19,20].

Based on these properties, Auriga et al. used grapevine pruning residues to create particleboards that, at 50% *w/w*, met European strength standards (EN 312 and EN 16368), while also reducing drilling forces, swelling, and water absorption [21]. In a similar manner, Paudel et al. developed eco-friendly, biodegradable packaging films with high transparency (83.7–84.3% mm⁻¹), strong tensile properties (15.4–18.2 MPa), and rapid soil biodegradability, demonstrating their potential as sustainable alternatives to conventional plastic packaging [22].

While pruning waste is often burned, composted, or mulched, improper management can lead to nutrient leaching and soil microbial imbalances. Notably, open burning of vineyard pruning waste emits a complex mixture of hazardous pollutants, including fine particulate matter (PM₁₀ and PM_{2.5}), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), heavy metals, and black carbon [23,24]. These emissions are well-documented contributors to respiratory and cardiovascular disease, mutagenicity, and short-term climate forcing. In addition, open burning releases substantial quantities of greenhouse gases, with CO₂ emissions exceeding 1.6 tons per ton of vine prunings. This practice implemented in most rural areas also elevates wildfire risk, particularly in drought-prone viticultural regions [25]. Lastly, the resulting ash is rich in nutrients and toxic elements (e.g., phosphorus, potassium, trace metals, and persistent organic pollutants) which can leach into soils and waterways, driving eutrophication and ecotoxicological impacts [24].

3.1.2. Winemaking

Destemming

Winemaking is a complex sequence of biochemical and mechanical processes, each contributing not only to the sensory profile of the final product but also to the generation of various organic and inorganic by-products [26]. More specifically, as seen in Figure 2,

wine production begins with destemming, a mechanical process that removes approximately 14% of the grape mass in the form of lignocellulosic stems and leaves, amounting to roughly 4 kg of stalks per 100 L of wine, and translating to millions of tons annually worldwide. These grape stems are rich in polymers (comprising 17–26% lignin, 20–30% cellulose, 15–25% hemicellulose, and 6–9% ash) and contain around 6% phenolic compounds including tannins, flavanols (e.g., catechin, galocatechin), hydroxybenzoic acids, flavonols, and stilbenes [5,27]. When discarded without proper management, this biomass can foster localized microbial activity, leading to foul odors and leaching of phenolic compounds into soil or water, potentially causing phytotoxicity, soil acidification, and oxygen depletion in aquatic systems.

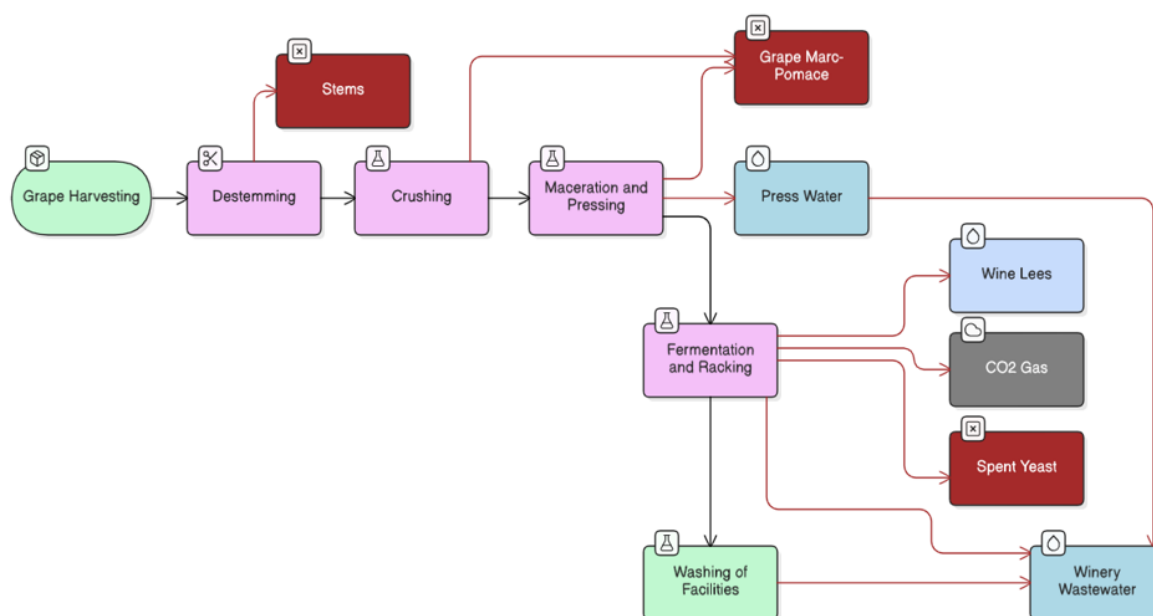


Figure 2. Winemaking steps, products and main by-products. (Color index: Purple → main wine-making stages, Light green → peripheral stages regarding winemaking, Light blue → mostly liquid by-products, Blue → winery wastewater, Gray → gaseous by-products, Red → solid by-products).

Crushing

The next step of winemaking is crushing, during which the mechanical rupture of grape berries releases the must, while care is taken to minimize seed breakage to prevent the release of bitter seed oils rich in unsaturated fatty acids and tannins. Grape pomace typically constitutes 20–25% of the processed grape weight and represents the largest fraction of solid waste with an estimated global production exceeding 8 million tons annually [28]. Its improper storage or disposal can lead to the generation of acidic leachates rich in organic acids (e.g., tartaric, malic, acetic acids), phenolic compounds, and sugars, which increase biochemical oxygen demand (BOD) and chemical oxygen demand (COD) in adjacent water bodies. This leachate can acidify soils and water, promote microbial oxygen depletion, and disrupt aquatic ecosystems, with documented cases of biodiversity loss linked to winery effluent discharge [29].

Maceration and Pressing

Afterwards, the maceration phase involves the extraction of phenolic compounds, pigments, and aromatic substances from grape skins into the must when producing red wine [26]. Although this process does not directly produce additional by-products, it alters the chemical profile of the remaining solids, particularly the pomace, thereby complicating their disposal or reuse. Grape pomace, which is the combined mass of skins, stems,

and seeds, remains a high-volume waste stream. Its composition, as well as its quantity, vary significantly due to multiple factors, including grape species, harvest timing, regional characteristics and the specific winemaking processes employed [5].

Typically, grape pomace contains 50–72% moisture, with insoluble residues composed of 16.8–24.2% lignin and less than 4% protein, while its cell walls are primarily made up of 37–54% pectic substances and 27–37% cellulose. Additionally, the pomace includes 15–52% seeds rich in fiber (up to 40%), essential oils (around 16%), protein (11%), tannins, and a high concentration of polyphenols, making it a valuable source of bioactive compounds [6]. Using response surface methodology, Meini et al., optimized an aqueous enzymatic extraction process for grape pomace. The results showed that, under optimal conditions of temperature, pH, and enzyme concentrations (pectinase, cellulase, tannase), phenolic yield increased by up to 66% and antioxidant capacity by up to 80%, with tannase releasing gallic acid, cellulase enhancing p-coumaric acid and malvidin-3-O-glucoside recovery [30]. In other studies, raw grape pomace is very often valorized through composting and vermicomposting [31]. For instance, in an autumn–winter open-pile process, Mattei et al. transformed white and red grape pomace into a stable organic fertilizer, reaching thermophilic temperatures of ~60 °C at neutral pH, obtaining a non-phytotoxic compost with high germination indices (144.2% and 139.8%), enriched microflora dominated by *Aspergillus* (80%), *Rhizopus* (10%), and *Penicillium* (17%), and nearly double CFU g⁻¹ in lyophilized compost. Their results indicated both strong fertilizing quality and suppressive potential against soil pathogens [32]. A different approach was utilized by Gubitosa et al., who synthesized gold nanoparticles (AuNPs) using an aqueous extract of grape pomace waste from *Vitis vinifera*, and subsequently repurposed the residual biomass as an efficient adsorbent for the removal of emerging contaminants, exemplifying a zero-waste, circular approach [33]. Similarly, Cisneros-Yupanqui et al. demonstrated that spent grape pomace (SGP) from Grappa production retains significant antioxidant activity and enzyme inhibitory effects related to non-communicable diseases, with some bioactivities diminishing post-distillation but notably improving after one month of storage, highlighting SGP's promising potential for food industry applications [34]. Maceration is followed by pressing, which separates the must from the pomace, yielding clarified juice and solid residues, including grape pomace and lees [26].

Alcoholic Fermentation and Racking

Alcoholic fermentation, the main and most crucial step in winemaking, whether spontaneous or yeast-inoculated, primarily emits carbon dioxide as a gaseous by-product. Although natural and expected CO₂ emissions from fermentation tanks can be substantial in large-scale wineries, they contribute to the carbon footprint of the sector [4]. In addition, spent yeast biomass from fermentation is also another by-product, typically settled into lees. If not recovered for valorization (e.g., as a nutrient supplement in animal feed or fertilizer), it becomes part of the solid waste stream.

Following fermentation, racking is carefully performed to separate the wine from the sediment (lees and wine mud) that has settled at the bottom of the vessel [26]. These sediments, containing yeast residues, tartrate crystals, and other colloidal particles, pose management challenges due to their high organic content and potential for microbial fermentation [16]. Further removal of residual suspended solids is achieved through fining, which involves the addition of fining agents (e.g., bentonite, gelatin, casein) [26]. Although effective, these agents often become contaminated during the process and must be discarded as specialized waste, which can introduce metal ions or allergens into ecosystems [27].

In the final stage, stabilization aims to maintain the product's properties and organoleptic characteristics and to prevent unwanted re-fermentation and chemical degradation [28]. Methods such as cold stabilization, heat treatment, sulfiting, and metal ion removal (e.g., iron and copper) are most commonly used. The sludge produced after cold stabilization and metal precipitation is often laden with salts and acids, which can lead to soil and groundwater contamination. More importantly, this stabilization sludge also incorporates the previously formed wine lees, thereby representing the final aggregated solid waste stream from winemaking operations [35].

Winery Lees and Wastewater

Winery lees, rich in dead yeast cells, tartaric acid crystals, residual grape solids, and phenolic compounds, represent a secondary waste product with high organic load and are typically separated through sedimentation or filtration [27]. Lees consist mostly of dead or autolyzed yeast cells, grape solids, tartaric acid precipitates, mannoproteins, and residual sugars. Chemically, they are rich in nitrogenous compounds, lipids, amino acids, and polysaccharides (β -glucans and mannans). Thus, they have great valorization potential for energy production, soil amendment and as additives [36].

More specifically, thermal or enzymatic autolysis can break down yeast cell walls to release mannoproteins and glutathione, both of which can be used in winemaking (ageing) to improve mouthfeel and oxidative stability, crucial organoleptic characteristics of wine. Additionally, solid–liquid extraction followed by ultrafiltration or resin adsorption can isolate bioactive peptides and antioxidants to be used as additives in foods and cosmetics [37]. Dimou et al. developed an integrated biorefinery approach using wine lees to produce antioxidants, tartrate, ethanol, and nutrient-rich hydrolysates, which supported high-yield poly(3-hydroxybutyrate) (PHB) production by *Cupriavidus necator*, achieving concentrations up to 30.1 g L⁻¹ with 71.3% intracellular content [38]. With a more circular economy mindset Kokkinomagoulos et al. valorized wine lees by optimizing autolysis conditions to produce a yeast extract substitute, achieving up to an 834% increase in free α -amino nitrogen (FAN), thus demonstrating their potential as nutrient sources or nitrogen modulators in winemaking [28].

In the biogas production sector, wine lees are often co-digested with grape pomace or winery wastewater in anaerobic digesters to optimize the carbon-to-nitrogen (C/N) ratio, thereby enhancing methane yield. Sevillano et al. investigated the application of electro-oxidation as a pre-treatment method to further improve biogas production. Their findings demonstrated a significant increase in methane output, reaching up to 330 L/kg of volatile solids after 1.5 h of treatment, compared to just 180 L/kg from untreated wine lees [36]. Additionally, in major winemaking countries such as Spain, France, and Italy, wineries have increasingly implemented aerobic composting of lees combined with grape stems, yielding nutrient-rich compost for vineyard soil amendment [39].

Finally, wastewater from winemaking operations is another significant environmental burden [4]. Generated from equipment cleaning and grape processing, winery wastewater typically exhibits high BOD (1000–5000 mg/L) and COD (2000–10,000 mg/L), with pH between 3 and 7 [40]. It contains dissolved sugars, ethanol, detergents, organic acids, suspended solids, and microbial biomass. Due to its high organic load and fluctuating composition, proper treatment and reuse strategies are critical [41].

3.1.3. Distillation Processes and Waste Generation

Distillation plays a critical role in determining both the quality and safety of distilled spirits by selectively removing toxic, low-boiling compounds from the final product [42,43]. As seen in Figure 3, during a typical distillation, the fermented substrate is heated and vaporized, and the condensate is separated into three sequential fractions: heads,

heart, and tails. The first cut/fraction collected is known as the “heads” or “foreshots” and contains low-boiling point volatile compounds, such as methanol, acetaldehyde, and ethyl acetate that are generally discarded due to their toxicity and undesirable organoleptic characteristics. Following the heads, the “heart” fraction is collected. This is the primary distillate intended for consumption and contains the bulk of ethanol (20–72% *v/v* ethanol, 30–45% of the distillate) along with desirable aroma and flavor compounds [44]. At the end of the distillation, the “tails” or “feints” are collected (10–15% of distillate) which predominantly contain higher alcohols including propanol, butanol, and isoamyl alcohol (~100–132 °C) [18]. The heads and tails fractions represent underutilized streams with significant potential for integration into biorefinery frameworks.

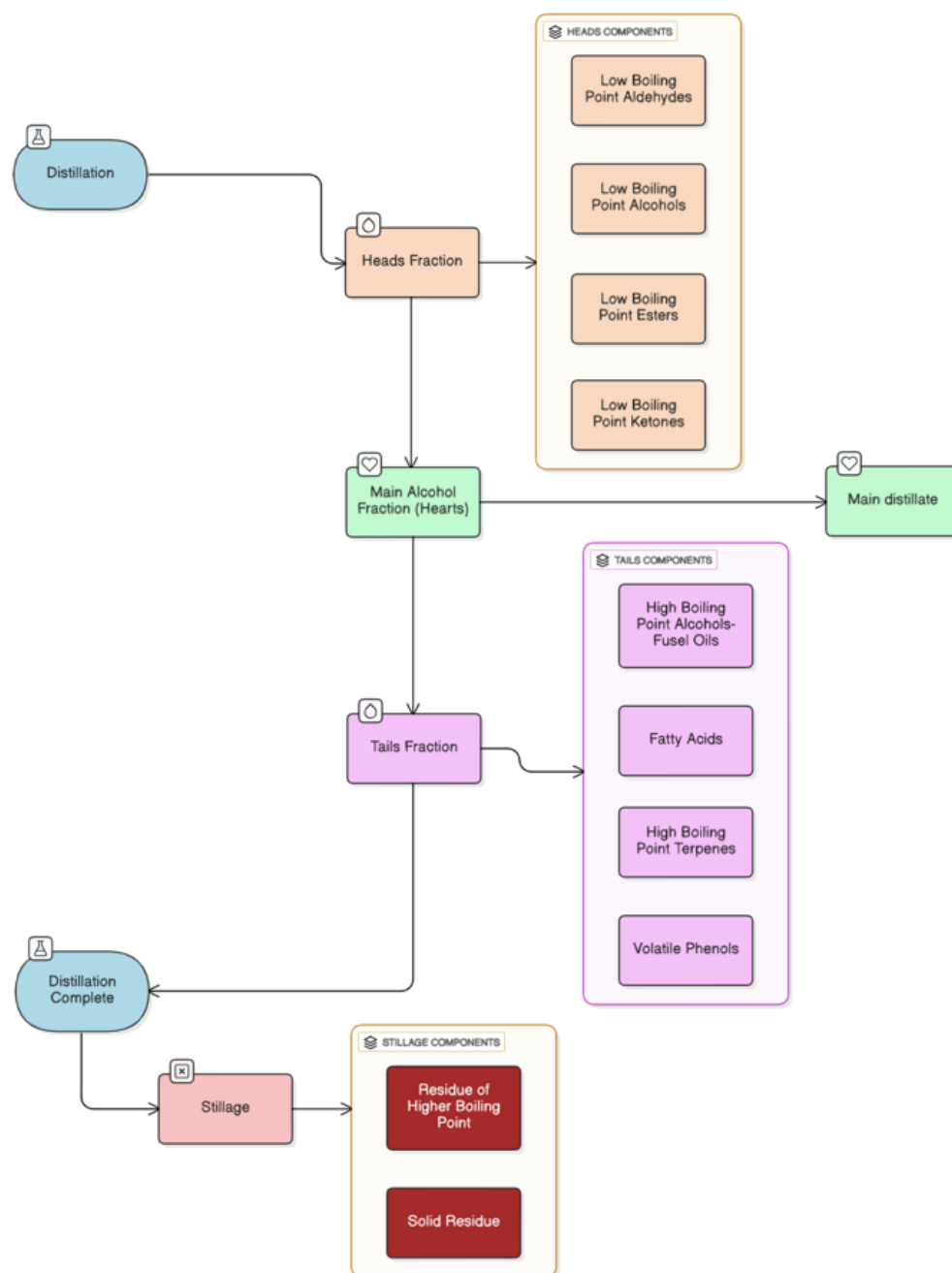


Figure 3. Distillation fractions and main by-products. (Color index: Purple → tails fraction and its main components, Light green → main distillate/product of distillation, Light blue → starting and ending point of distillation, Light Orange → heads fraction and its main components, Red → stillage and its components).

These compounds can be selectively recovered through advanced separation techniques such as fractional distillation, liquid–liquid extraction, and pervaporation membranes, enabling their reuse as chemical solvents, fuel additives, or feedstocks for bio-based chemical synthesis. For instance, methanol recovered from head fractions can be classified as bio-methanol and used directly or in transesterification reactions for biodiesel production. Additionally, second-stage heads and tails, containing residual ethanol and fusel oils, may be valorized directly as biofuels or integrated into industrial solvent formulations [17]. Beyond direct chemical recovery, residual aqueous-organic streams can be subjected to anaerobic digestion, with operational pH conditions tunable to favor either biohydrogen (pH 3–5) or methane (pH 6–8) production [17,43]. Moreover, as studied by Da Porto et al., foreshots and tails fractions are commonly recycled into subsequent distillation cycles to increase ethanol concentration in the “heart” fraction by 4%, alongside rises of 7% in higher alcohols, 13% in esters, and 10% in aldehydes, enhancing the organoleptic profile of the distillate while reducing discard volumes and improving overall product recovery [44]. Lastly, the incorporation of water recovery technologies further enhances the sustainability of these processes. Collectively, the targeted valorization of heads and tails not only reduces the environmental impact of grape distillation waste but also aligns with circular economy principles by transforming these by-products into high-value energy carriers and platform chemicals [45].

While the primary objective of distillation is the recovery of ethanol or the production of alcoholic beverages with elevated ethanol concentrations, the process can also generate by-products in volumes up to 15 times greater than that of the target distillate [40,46].

The primary residue left behind in the distillation vessel after vapor removal, is known as stillage, a dark, viscous liquid with high concentration of suspended solids and acidic pH (3.5–5). Typically contains high COD (~29,000–44,000 mg/L), BOD (~10,000–15,000 mg/L), potassium (~2.1 g/L), traces of ethanol, organic acids and low residual ethanol [43]. Due to its acidity (pH ~3.88) and high salinity (~3.25–3.27 ppt after filtration), direct discharge without treatment is harmful to the environment and not viable long-term [47].

To mitigate these impacts, the stillage can be effectively treated via anaerobic digestion (AD) in continuously stirred tank reactors or upflow anaerobic sludge blanket reactors to generate biogas with 55–70% methane content. The digestate, once stabilized, can be used as a liquid organic fertilizer. Beyond AD, advanced treatments, such as electrodialysis and membrane filtration (nanofiltration or reverse osmosis), can also recover water and concentrate nutrients for precision agriculture applications [48]. In a more creative approach, Roy et al., used distillery stillage as a sustainable, nutrient-rich substrate for cultivating *Rhizopus microsporus var. oligosporus* via solid-state fermentation, enabling efficient production of pure mycelium materials with tunable properties [49].

Solid residues, namely exhausted-spent pomace, remain after the distillation of grapes. This material typically has a moisture content reduced to 20–30%, compared to 50–72% in fresh pomace and is rich in lignin and cellulose, along with residual lipids, waxes, and condensed tannins, components that contribute to its high structural recalcitrance [7]. Because of its resistance to microbial degradation, exhausted pomace is commonly disposed of through composting, vermicomposting or incineration. In a 56-day pilot-scale study, Gómez-Brandón et al., demonstrated that distilled grape pomace is a suitable feedstock material for vermicomposting. In their research, early increases in *Eisenia andrei* biomass, optimal pH and EC from day 14, and rapid declines in microbial activity and polyphenols, yielded a nutrient-rich vermicompost that meets quality standards for safe agricultural use [50]. However, there is a growing interest in valorizing this lignocellulosic by-product for more sustainable applications. Many studies have demonstrated its potential in the production of biochar via pyrolysis, offering soil amendment benefits and

carbon sequestration potential. In addition, its rich lignin and polysaccharide content make it a promising feedstock for emerging bioplastic technologies [51].

Several studies have explored the simultaneous valorization of both biomass and liquid by-products to enable complete residue utilization, reduce carbon emissions, and enhance environmental performance, thereby advancing circular economy principles and improving the life cycle profile of the resulting materials. For example, Barbanera et al. demonstrated that hydrothermal carbonization (HTC) of vine pruning, exhausted grape pomace, and stillage under optimized conditions (246.3 °C, 1.6 h, S:L ratio of 0.066) produced hydrochar with 52.64% mass yield, 0.60 fuel ratio, and 1.21 energy densification yield. The process also generated a phenol-rich liquor (21.88 mg GAE/g) and highlighted that using stillage as a moisture source did not negatively affect efficiency or product quality [35].

All in all, these integrated waste streams form an ideal substrate for advanced thermochemical conversion, positioning pyrolysis and its primary product, biochar, as pivotal technologies for next-generation valorization.

3.2. Biochar Production, Applications, Modifications and Regeneration

3.2.1. Biochar Production

Among the various valorization strategies of solid waste streams, biochar has garnered considerable research attention over the past decade owing to its multifunctional properties, enabling diverse applications in fields such as agriculture, sensors, energy storage devices, catalysis, and adsorption technologies [8]. Biochar is defined as a carbon-rich, porous material produced through the thermochemical conversion of biomass under limited oxygen conditions. It is primarily composed of aromatic carbon structures, which provide high stability and resistance to degradation, making it an effective long-term carbon storage [51,52]. Its valuable physicochemical properties like high surface area, porosity, cation exchange capacity (CEC), and nutrient content, vary widely depending on the source biomass and production method (e.g., pyrolysis conditions) [11,53].

Pyrolysis is the thermal decomposition of organic materials in an oxygen-limited or oxygen-free environment, which prevents combustion and facilitates the conversion of biomass into biochar, bio-oil, and syngas. It represents a versatile technology for biomass valorization, enabling the generation of energy and carbon-rich solid products simultaneously [8]. Pyrolysis processes are typically classified into three main types based on temperature and residence time: slow, fast, and flash pyrolysis; however, ongoing research continues to expand this spectrum to include innovative variants such as microwave-assisted pyrolysis, co-pyrolysis, wet pyrolysis, etc. [52,53]. Slow pyrolysis, characterized by low heating rates and long residence times, maximizes biochar yield, while fast and flash pyrolysis employ rapid heating and short residence times to optimize bio-oil production. Each type offers distinct advantages depending on the desired product distribution and feedstock characteristics [53].

The quality and yield of biochar are heavily influenced by pyrolysis operational parameters (e.g., temperature, heating rate, residence time, and pressure) and the structure of the feedstock. Higher pyrolysis temperatures generally reduce biochar yield but increase carbon content, aromaticity, and surface area, enhancing its stability and sorptive capacity. Conversely, lower temperatures favor greater biochar mass production with more volatile organic compounds retained [15]. Several studies have reported that increasing the pyrolysis temperature from 300–400 °C to 600–800 °C leads to a progressive decrease in biochar yield due to enhanced devolatilization and secondary carbonization reactions. For example, according to Ferreira et al. grape pomace biochar yields decreased from approximately 51% to 30% when the carbonization temperature increased from 300 to 800 °C, while biochars produced at 400–500 °C exhibited properties more suitable for

agricultural applications [54]. Additionally, increasing heating rates and shortening residence times generally reduce biochar yields by promoting rapid release of volatile compounds, whereas slower pyrolysis conditions favor char formation and the development of porous carbon structures. In another study by Aktas et al., fast-pyrolysis experiments on grape pomace were conducted between 400 and 600 °C, where both increasing temperature and heating rate resulted in lower biochar yields, highlighting the importance of optimizing process conditions according to the desired end use [55]. Atmosphere is another critical factor, since oxygen's absence promotes the decomposition of organic matrix, and the choice impacts the yield and properties of the pyrolysis products. Common atmospheres include inert gases like nitrogen or argon, or reactive gases like CO₂ or steam, which can modify surface chemistry. In a study by Azuara et al., pressurized pyrolysis of vine shoots under CO₂ produced stable, porous biochar with similar yields to N₂-based pyrolysis, while enhancing CO production and surface area through the reverse Boudouard reaction [56].

In a similar manner, feedstock characteristics such as moisture content, elemental composition, lignin, cellulose, and hemicellulose content also play a critical role, since lignin-rich materials typically produce biochars with higher fixed carbon and greater structural integrity [11]. Mourgkogiannis et al. investigated biochars produced from several biowastes, including grape seeds remaining after wine production and distillation, coffee residues, and rice husks, using identical pyrolysis conditions (850 °C, 1 h, oxygen-limited atmosphere). Despite being produced under the same thermal regime, the resulting biochars exhibited substantial differences in specific surface area (367–870 m² g⁻¹), pore structure, ash content, and sorption capacity, highlighting the critical role of feedstock composition in determining biochar quality [11]. Lastly, co-pyrolysis and biochar modification of any kind can further enhance its efficiency in a specific application [53,57]. Thus, it is evident that optimizing these parameters is essential to tailor biochar properties for specific uses [15].

3.2.2. Biochar Applications

It is well known that the type of biochar application and its efficacy depend primarily on its inherent properties, which are determined primarily by the feedstock type and pyrolysis conditions [11,53]. In agriculture, biochar is widely used to enhance soil fertility, nutrient retention, and microbial activity, while in material science, it serves as a reinforcing filler or additive in polymer composites and construction materials, due to its structural stability and lightweight nature [9,58]. As a fuel or energy carrier, biochar also exhibits high fixed carbon content and energy density, making it a promising renewable solid fuel or precursor for syngas production [59]. Furthermore, its resistance to degradation allows for long-term sequestration of atmospheric CO₂ in sediments, making it an ideal carbon sink [60]. Regarding its chemical applications biochar's highly porous structure and tunable surface chemistry facilitate the adsorption of a wide range of organic and inorganic pollutants [10,61], while also serving as a robust substrate or catalytic material, emphasizing that its functional groups, doped heteroatoms, and metal loadings serve as key active sites in persulfate activation, Fenton-like, and photocatalytic reactions in heterogeneous catalytic systems [62,63]. Lastly, emerging research highlights biochar's potential in pharmaceutical and biomedical fields (e.g., drug delivery, wound healing, biosensing) due to its biocompatibility, adsorptive properties, and customizable surface functionalities [64]. Various applications of biochar are illustrated in Figure 4.

Biochar derived from viticulture residues, winemaking by-products, and distillation waste, is most commonly applied in soil amendment, renewable energy production, and adsorption. Kwoczynski et al., utilized grape pomace biochar, which due to the high potassium content (30 ± 3 g/kg) and other nutrients, compared to other biochars from other

studies, positively influence lettuce [65]. Martínez-Gómez et al. observed also how effective it was for root knot nematode control [66]. Additionally, Ibn Ferjani et al. found that biochar derived from exhausted grape pomace (especially at 500 °C) can act as a promising slow-release biofertilizer. This study showed that the biochar enhanced nutrient release (especially potassium, calcium and phosphorus) and retention in soil compared to other biochars from lignocellulosic materials presented in previous studies (such as Mallee wood and leaf biochar, wheat straw biochar, wood chip biochar mixture of wood chip and beech trees biochars, and sugarcane straw biochar) [67]. In a recent study, the combined use of *Trichoderma* and biochar from grapevine prunings or biochar from grape pomace, increased vineyard soil microbial biomass carbon by 569% and boosted grape productivity, enhancing soil fertility and grapevine growth [68].

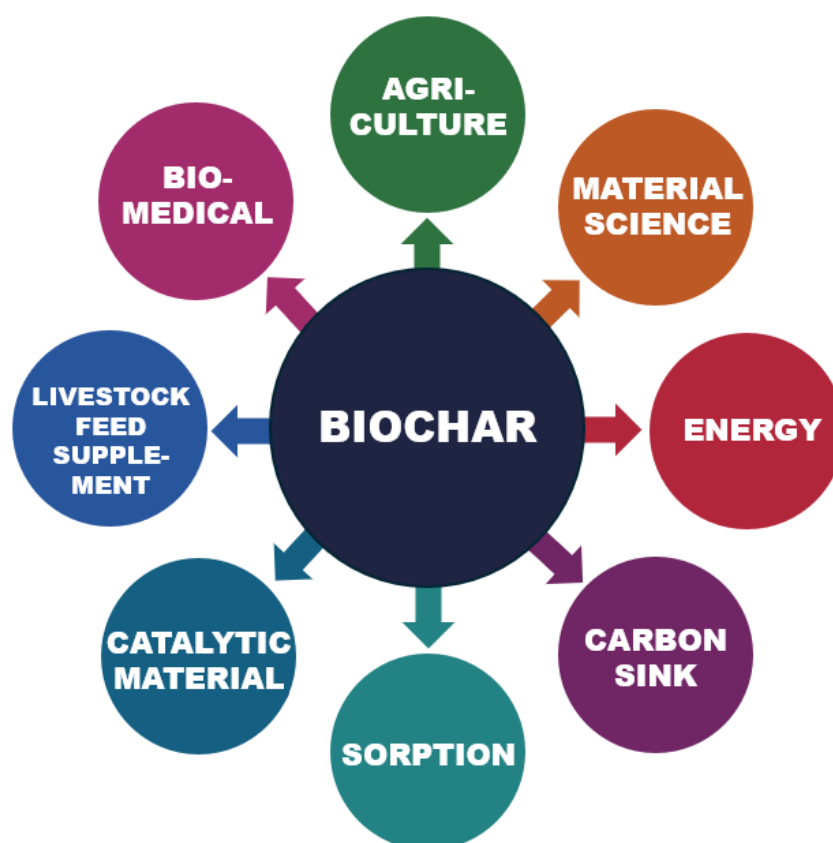


Figure 4. Biochar applications in several sectors.

As for energy production, Kyriakou et al. utilized biochar from vineyard prunings (pyrolyzed at 500 °C), which enhanced yeast immobilization and boosted ethanol productivity by 36–52%, demonstrating its effectiveness in improving biofuel production through microbial fermentation. Olive kernels, sewage sludge and seagrass residues were also evaluated and compared, highlighting the efficiency of vineyard prunings and seagrass residues as support for biocatalysts [69]. Lastly, biochar from grape pomace can also be utilized as a low-cost and eco-friendly biosorbent, showing high efficiency in removing toxic heavy metals like Pb, Cd, Hg, and Cu from water and soil [12]. According to the study by Prelac et al., biochar from grapevine pruning residues showed strong adsorption of polyphenolic compounds from viticultural waste, with recovery rates of 41.5% of caffeic acid, 61.8% of gallic acid, and 91.4% of oleuropein [13]. Moreover, a portion of the grape pomace’s phenolic profile, entangled within the lignocellulosic matrix, is partially retained in the resulting biochar as residual phenolic compounds embedded in the aromatic carbon structure. Thus, this chemical feature may contribute to enhanced affinity

and specific interactions with a variety of target pollutants through π - π interactions, hydrogen bonding, or metal chelation mechanisms as suggested in a study done by Abdoul-Latif et al. on olive waste derived biochar and its phenolics [70]. Table 1 presents some case studies about applications of biochar from grape processing waste.

Table 1. Biochar from different types of grape residues and their applications.

Type of Bio-mass	Pyrolysis Conditions	Yield (%)	Application	Results	References
Grape pruning residue (GPR)	400 °C, 24 h, layers upon layers	30.8 ± 0.02	⊙ Caffeic acid (CA), Gallic acid (GA), and Oleuropein (OLP)	5.73 mg/g CA, 3.90 mg/g GA, 3.17 mg/g OLP	[13]
	500 °C, 2 h, N ₂	-	Filler/nucleating agent in PLA biocomposites	Tensile and impact strength increased by 41.4% and 32.1%	[71]
	220 °C, 250 °C, 280 °C, 0–10 min	220 °C → 79.90 250 °C → 72.35 280 °C → 70.10	* Cost-effective biochar production	Energy recovery of 87.3% ± 1.7% at low temperatures	[72]
	450–500 °C (proprietary protocol)	-	⊙ <i>E. coli</i> × prebiotic for Lactobacillus species	Rich in antimicrobial and antioxidant compounds, inhibition of <i>E. coli</i> and quorum sensing genes, prebiotic activity	[73]
	Multistage: 20–180 °C for 30 min, 180–340 °C for 60 min, 400 °C for 90 min	~21	* and carbon sequestration	>50% increase in heating value ~60% increase in carbon content	[74]
	700, 800, and 900 °C, 1 h, N ₂	700 °C → 32.30 800 °C → 31.57 900 °C → 30.65	⊙ Cu(II) from aqueous media	BC dosage 1.5 g/L, 96.56% removal in 60 min	[75]
Grape pomace, marc, husks, bagasse	650 °C, 2 h	-	⊙ 2-mercaptobenzothiazole (MBT) from aqueous media	~99% removal of MBT at 0.8 g/L BC	[76]
	300, 500, and 700 °C, 2 h, N ₂	-	⊙ Tetracycline (TC) from wastewater	17.38 mg/g of TC	[77]
	500 °C, 30 min, N ₂	-	Δ and assessment of leaching behavior	Increased K by 76%, reduced heavy metal leaching by 40–95%, raised pH, reduced COD	[78]
	350 °C or 700 °C, 2 h, N ₂	BC700 → 28.4 BC350 → 45.7	Control of root-knot nematodes (RKNs)	0.75% w/w BC350 enhanced tomato production by 46% and reduced nematode reproduction by 39–42%	[66]
	550 °C, 3 h, N ₂	-	⊞ for supercapacitors	446 F/g (1 M H ₂ SO ₄), 345.5 F/g (6 M KOH), 310 F/g (1 M Na ₂ SO ₄) at 0.5 A/g	[79]
Exhausted grape pomace (EGP)	450, 500, 550 °C, 1 h, N ₂	450 °C → 41.1 500 °C → 39.5 550 °C → 37.7	Δ and plant growth (ryegrass)	Nutrient-rich & BC EGM450 biochar improved ryegrass growth by 16%	[80]

Exhausted grape pomace and stalks Grape pomace and its secondary processing wastes Grape seeds, defatted grape seeds, wood stems, whole grape seeds	300, 400, 500 °C, 30 min, N ₂	-	Δ and ⊙ pathogen	15 t/ha dose improved water retention and increased pH and EC in 60 d, inhibited <i>Fusarium</i> and <i>Phytophthora</i>	[81]
	450 °C, 1 h, N ₂	-	⊞ Polyphenol (TPP) from wine wastewater	84.3% TPP removal	[82]
	600 °C, 2 h	-	Support in catalyst used for dehydration of sugars into 5-HMF	5-HMF yield ~41.8% & catalyst recyclability ≥ 5 cycles	[83]
	300, 500, and 700 °C, 2 h, N ₂	300 °C → 55.1 500 °C → 33.2 700 °C → 31.8	⊙ Pb from aqueous media	66.5% of Pb (300 mg/L) in 30 min	[84]
	300 °C, 3 h or 24 h, N ₂	~35	⊞ Filler in electrically conductive composites	Composites with 25% w/w BC could substitute the composite with 30% w/w of G45 graphite	[85]

⊙ sorption, ✱ energy recovery, ⊞ electrode material, Δ soil amendment, ⊙ resistance, × enhancement.

3.2.3. Biochar Modification Methods

Beyond the inherent properties dictated by the feedstock type and pyrolysis parameters (e.g., temperature, heating rate, residence time), the functional performance of biochar can be substantially improved through modification techniques [57]. These methods aim to tailor the physicochemical characteristics of biochar (surface area, porosity, surface functional groups, and mineral content) in order to enhance its suitability for specific environmental, agricultural, or industrial applications. Furthermore, modifications may take place pre-treatment, post treatment, or in situ [86].

Activation methods, a type of modification methods, are primarily concerned with increasing the surface area, pore volume, and structural accessibility of biochar, which are broadly classified into physical and chemical subcategories [86]. Physical activation typically involves high-temperature treatment prior to pyrolysis in the presence of oxidizing gases such as steam, CO₂ or microwave irradiation [87,88], which enhances porosity and surface accessibility [52]. Chemical activation, on the other hand, entails impregnating biomass or biochar with chemical agents prior to or during pyrolysis (e.g., potassium hydroxide (KOH), phosphoric acid (H₃PO₄), or zinc chloride (ZnCl₂)) [89–91], which promotes the formation of microporous structures and increases surface functionalization [57]. The primary goal of activation is to enhance adsorption capacity, diffusion efficiency, and surface reactivity by generating a large and accessible surface area [14].

In a broader range, modification refers to post-pyrolysis treatments aimed at tailoring surface chemistry without significantly altering the porous structure-porosity, the surface chemistry or the elemental composition of biochar. This includes the introduction of specific functional groups (e.g., –OH, –COOH, –NH₂), doping with heteroatoms (e.g., N, S, Fe), or the deposition of nanoparticles to tailor the surface properties for a particular application [79,84,92–95]. Such chemical modifications aim to improve properties like hydrophilicity/hydrophobicity balance, cation exchange capacity (CEC) and surface charge, making the material more effective in applications such as contaminant adsorption, soil

amendment, or environmental catalysis [14]. Furthermore, physical and biological modification methods, such as ultrasound, plasma treatment, electrochemical techniques, and microbial or enzymatic treatments, have emerged as the most eco-friendly post-pyrolysis approaches to tailor biochar properties with improved efficiency and without the use of chemicals [96].

Apart from the primary objective of biochar modification, the overall effectiveness of these enhancement strategies is significantly influenced by several critical parameters. These include the type and concentration of activating or modifying agents, the pre-treatment of the feedstock, the duration and temperature of the treatment, and the mass ratio between the biochar precursor and the activating or modifying agents [97].

However, it is important to recognize that many of the chemicals employed in these processes, particularly strong acids, bases, and organic solvents, may pose environmental and health risks if not properly managed. Consequently, the selection of activating/modifying agents, as well as the implementation of effective recovery, recycling, and waste management practices, is crucial to ensuring the environmental sustainability and safety of biochar enhancement processes [14,52]. Various modification methods and their applications are shown in Table 2.

Table 2. Case studies of enhancing biochar’s abilities through physical activation, chemical activation and other modifications methods.

	Type of Activation/Modification Method	Activation/Modifying Agents	Feedstock Type	Pyrolysis Conditions	Application & Results	References
Activation	Physical	CO ₂	Vine wood waste	600 °C, 30 min, N ₂	Supports for Ni, Al catalysts: 97% maximum efficiency	[98]
			Vine shoots (<i>Vitis vinifera</i>)	500 °C, time varied	⊙ 172 mg/g Acetamiprid 92 mg/g Metalaxyl 210 mg/g Penconazole	[87]
			Grapevine stalks	700 °C, 1 h, low-oxygen conditions	⊙ Methylene blue (MB), efficiency up to 100%	[91]
	Chemical	ZnCl ₂	Grape pomace	600 °C, 3 h, N ₂	⊞ Supercapacitor electrode: 29 F g ⁻¹ (2 mA)	[89]
			Grape pomace	450 °C with ZnCl ₂	⊞ Supercapacitor electrode: 41 F g ⁻¹ (2 mA)	
		H ₃ PO ₄	<i>Vitis vinifera</i> leaf litter	600 °C, 1 h, N ₂	⊙ Phenanthrene: 94.12 mg/g 47.08% removal	[99]
			<i>Vitis vinifera</i> leaf litter	600 °C, 1 h, N ₂	⊙ Phenanthrene: 89.13 mg/g, 58.4% removal	
			Grape stalk waste from winery	600 °C, 1 h, N ₂	⊙ Cu(II) ions from water: 92.21% removal	
			Grape seeds waste	800 °C, 3 h, N ₂	⊙ Paracetamol: 17.3 mg/g	
			Burmese grape seeds	500 °C, 3 h, N ₂	⊙ MB: 166.30 mg/g, ~85% removal	
		H ₂ SO ₄	Grape wood waste	750 °C, 1 h	⊙ Reactive Red 2: 96.83% in 90 min	[102]
		H ₂ O ₂	Grape wood pruning waste	350, 500, 900 °C, 2 h, N ₂	⊙ Cyhalofop: ↑ ef. by 30%, ⊙ Clomazone: ↑ ef. by 5%	[103]
		KOH	Grape pomace	600 °C, 3 h, N ₂	⊞ Supercapacitor electrode: 117 F g ⁻¹ (2 mA)	[89]

Modification	N-doping	Urea	Grape pomace	550 °C, 3 h, N ₂	☐ Supercapacitor electrode: 446 F g ⁻¹	[79]
				600 °C, 3 h, N ₂	☐ Supercapacitor electrode: 139 F g ⁻¹ (2 mA)	[89]
		Fe(NO ₃) ₃ ·9H ₂ O	Exhausted grape pomace & Grape stalks	600 °C, 2 h	Catalytic support for fructose dehydration/conversion to 5-HMF: yield ~41.8% & recyclability ≥ 5 cycles	[83]
	Fe doping	Fe(NO ₃) ₃	Grape seeds	600 °C, 2 h, N ₂	⊙ As: ↑ sorption capacities 6.8–7.7 times	[104]
		FeSO ₄ ·7H ₂ O	Grape stalk and grape husk	600 °C, 30 min, N ₂	↑ SSA: 12–65%	[95]
		KOH	Grape pomace	600 °C, 2 h	⊙ CO ₂ : 26.8 mmol/g at 0 °C/30 bar	[105]
	Chemical modification with base	NaOH	Grape stalks	350 °C, 1 h	Support for MnFe ₂ O ₄ @Zn-Al LDHs@Cel@AGB nanocomposite for MB (97.4%) and Hg ²⁺ (84%)	[92]
	Chemical modification with base (microwave assisted)	NaOH	Burmese grape peel	-	⊙ Ciprofloxacin: 58.9 mg/L in 54 min	[106]
	Chemical modification with solvent wash and base	Ethanol and NaOH	Grape stalks	550 °C, 2 h	⊙ Meropenem: ↑ Removal Efficiency by 50–65%	[93]
			Grape pomace, stalks, seeds & pulp	650 °C, 830 min, inert atmosphere	⊙ Ivermectin: 46.6 mg/g ⊙ Diclofenac potassium: 49.2 mg/g	[94]
		H ₃ PO ₄	Grape pruning waste (branches)	300 °C, 2 h	⊙ Cd ²⁺ : 7.02 mg/g. 84.62% removal	[107]
	Chemical modification with acid	HNO ₃	Grape seeds	600 °C, 2 h, N ₂	⊙ As: ↑ × 6.8–7.7 compared to raw biochar	[104]
Chemical Surface Modification		HCl	Grape pomace	300, 500, 700 °C, 2 h, N ₂	⊙ Tetracycline (TC): 17.38 mg/g	[77]
		Ami-nopropyltriethoxysilane (APTES) in ethanol and the enzyme lacasse	Grape seeds	750 °C, 2 h, N ₂	Support for laccase immobilization for 100% degradation of Acetaminophen (APAP) 90 min, Sulfamethoxazole (SMX) in 30 min and TC in 5 h	[108]

⊙ sorption, ☐ electrode material, ↑ increase, × times increase.

Biochar Modification by Solvent Treatment

Solvent treatments using organic compounds such as methanol, ethanol, acetone, or dimethylformamide (DMF) do not primarily induce porosity but are employed to alter the surface chemistry of biochar, often through the removal of loosely bound organic impurities, functional group transformation, or enhancement of hydrophilicity/hydrophobicity, and such their use is considered a light modification method [109,110]. Unlike purely thermal or gas-phase activation processes, organic solvent treatments can induce physicochemical changes through selective solubilization of labile compounds and interactions with oxygen-containing surface functional groups [111]. These mechanisms may result in

partial restructuring of pore networks, modification of surface polarity, and redistribution of functional groups on the biochar surface [112,113].

More precisely, changes in surface chemistry are primarily associated with the extraction or transformation of residual extractives, tars, and low-molecular-weight organic compounds originally present in the biochar matrix. Depending on the polarity and chemical composition of the solvent, this process can increase or decrease the density of oxygen-containing functional groups, thereby influencing hydrogen bonding capacity and surface reactivity [112,113]. In addition, solvent penetration into the carbon matrix may promote pore opening and blockage removal, which can alter micro- and mesoporosity and consequently affect adsorption capacity. Furthermore, surface wettability is also strongly influenced by solvent treatment, as variations in functional group composition and surface polarity modify hydrophilic–hydrophobic balance. This effect is particularly relevant for adsorption processes involving aqueous media, where improved wettability enhances accessibility of internal adsorption sites [111,114].

For instance, Masrura et al. reported that sewage-sludge biochars modified with DMSO, deep eutectic solvents, or ionic liquids exhibited markedly enhanced selective adsorption performance, achieving capacities of $196.08 \mu\text{g g}^{-1}$ (AZ), $263.16 \mu\text{g g}^{-1}$ (CPX), $81.30 \mu\text{g g}^{-1}$ (SMX), $370.37 \mu\text{g g}^{-1}$ (TMP), and $833.33 \mu\text{g g}^{-1}$ (TC) in urine, although regeneration efficiencies declined to <30% after three cycles due to fouling and by-product accumulation [115]. With the same mindset, Granja et al. showed that dichloromethane-washed biochar derived from exhausted grape seeds (bSU) significantly enhanced the performance of a carbon-paste electrode (E-bSU) for fenamiphos detection, yielding a sixfold increase in analytical signal, low LOD/LOQ with excellent linearity, and high selectivity and repeatability with recoveries of 99–110% [116].

Methanol is another solvent used for biochar modification. Jing et al. demonstrated that alkaline pretreatment followed by methanol esterification of rice-husk biochar produced a MeOH-modified material with substantially improved tetracycline removal performance, achieving a 45.6% increase in adsorption capacity within 12 h, a 17.2% reduction in equilibrium time, and a doubled filtration volume relative to the original biochar, attributable to enhanced surface O-functional groups that strengthened π – π interactions [110]. Utilizing the same solvent, Ai et al. reported that orange-peel biochar subjected to acid washing followed by methanol esterification and Fe_3O_4 incorporation yielded a magnetically separable $\text{CH}_3\text{OH-OP-char/Fe}_3\text{O}_4$ composite with markedly enhanced adsorption of ibuprofen (58.12 mg g^{-1}) and sulfamethoxazole (60.90 mg g^{-1}), representing a 102.72–163.18% improvement relative to unmodified OP-char [117]. Also, Keshiknevisrazavi et al. demonstrated that walnut-shell biochar activated via methanol soaking (WBCM) achieved enhanced tetracycline removal from soil, increasing its removal efficiency from 46.5% to 80.4%, while mitigating antibiotic toxicity and partially restoring soil biological activity, highlighting its potential for soil amendment in antibiotic-contaminated environments [118].

Recently, eutectic solvent (DES) activation has also attracted scientific interest, in which ionic fluids are used (formed by combining a hydrogen bond donor and acceptor) to enhance biochar properties, such as with DES-glycerol (choline chloride and glycerol). For example, using tea-waste biochar as a precursor, Mashoene et al. demonstrated that surface modification with reduced graphene oxide and deep eutectic solvents (DES-CTAB or DES-glycerol), followed by sucrose-assisted thermal treatment, produced Biochar/rGO/DES composites that enhanced adsorption of zidovudine and phenol, with the Biochar/rGO/DES-glycerol material showing the highest removal efficiency [119].

In this context, distillation by-products (heads and tails) can be used as modifying agents, since their chemical composition (rich in ethanol, higher alcohols, esters, residual organic acids, etc.) can further influence biochar surface transformations [18,47]. Polar

components may promote functional group exchange reactions, whereas non-polar fractions may enhance swelling effects or facilitate the removal of hydrophobic residues from the carbon surface [120–122].

Finally, solvent modification can also serve as a pre-treatment step to improve the efficacy of subsequent chemical activation or functionalization processes, particularly when biochar is intended for high-value applications such as catalysis, drug delivery, or advanced adsorption systems [14].

3.2.4. Biochar Regeneration and Sustainability

Biochar deactivation is commonly associated with the saturation of active sites and pore blockage by accumulated contaminants. However, additional mechanisms may significantly affect its long-term performance and sustainability. When biochar is employed under severe operating conditions, particularly in catalytic and thermochemical conversion processes, structural deterioration of the carbon matrix may occur through thermal degradation, pore collapse, alteration of crystal lattices of the compounds, loss of surface functional groups, and mechanical breakage during use [120,121]. These phenomena can reduce SSA, alter porosity, and decrease the availability of active sites when biochar is used as catalyst's substrate, ultimately diminishing its performance. In a study by Argyle and Bartholomew [120], they highlighted thermal, chemical, and mechanical degradation as major causes of catalyst deactivation, while more recent studies on biochar-based catalysts have identified carbon deposition, structural instability, and active-site leaching as critical deactivation pathways during biomass conversion processes [120–122].

Furthermore, since biochar's highly porous structure and extensive surface area make it an effective sorbent for capturing pollutants from soil and water, the contaminants trapped within used biochar also pose a significant environmental risk. More specifically, these adsorbed pollutants can become a source of secondary contamination if the used biochar is not managed appropriately, potentially leading to the release of harmful compounds back into ecosystems. To address this problem, regeneration techniques are essential to restore biochar's sorption capacity while safely immobilizing or removing bound contaminants, thereby enabling its repeated use [123].

Consequently, regeneration strategies should not focus solely on contaminant removal but also on restoring or preserving the structural integrity of the biochar. Common regeneration approaches include thermal treatment, steam regeneration, solvent extraction, chemical washing, oxidative re-activation, and microwave-assisted regeneration. Although these methods can effectively recover adsorption or catalytic capacity, excessive regeneration may further modify pore structure and surface chemistry, emphasizing the need to optimize regeneration conditions in order to maximize biochar lifespan and overall process sustainability [120].

More specifically, biochar regeneration is the reverse process of adsorption and is primarily based on two principles: adsorbate desorption and adsorbate decomposition. Several regeneration techniques based on these principles have been developed and used, including thermal, plasma, chemical, microwave irradiation, and supercritical fluid regeneration [123]. Thermal regeneration is considered the most effective and widely used industrial method, wherein adsorbates are decomposed at high temperatures, with efficiency increasing alongside pyrolysis temperature [124]. Conversely, chemical regeneration employs acids or bases to remove adsorbates, often recovering them in transformed forms. However, its regeneration efficiency generally remains below 80% [125]. Plasma regeneration methods employ cold plasma to generate reactive species such as radicals and ions that degrade adsorbed contaminants on biochar surfaces under mild conditions [126]. Microwave irradiation utilizes electromagnetic energy to uniformly heat biochar

internally, preserving pore structure while efficiently decomposing trapped organics, offering enhanced control and reduced thermal inertia compared to conventional heating. Consequently, this method enables rapid regeneration with a lower risk of secondary pollution [127]. In certain cases, a combination of regeneration techniques is employed either separately for comparison or on the same used biochar. For instance, Baaloudj et al. utilized chemical oxidation with peroxymonosulfate (PMS), H_2O_2 , and peroxydisulfate (PS), where the process was enhanced through thermal regeneration or ultrasound irradiation [128].

Beyond contaminant removal, regeneration strategies for vitivinicultural and other biomass derived biochars focus on restoring porosity and surface functionality to recover their adsorption and catalytic performance. For this purpose, several modification methods of those described in this section have been employed. Steam and CO_2 re-activation have been reported to partially reopen blocked pore networks and increase specific surface area by promoting controlled carbon gasification, which is particularly relevant for biochars produced from lignocellulosic residues such as grape pomace and grapevine pruning waste [129]. Chemical re-activation using oxidizing or alkaline agents (e.g., H_3PO_4 , KOH , and H_2O_2) can further enhance pore development while restoring oxygen-containing functional groups that are essential for metal binding and organic contaminant adsorption [130,131]. In grape pomace-derived biochars, surface oxidation treatments have been shown to significantly increase surface polarity and adsorption capacity for organic pollutants due to the regeneration or introduction of carboxylic and hydroxyl groups. Similarly, studies on lignocellulosic agricultural biochars, including vine-pruning residues, report that thermal or chemical re-activation can partially recover pore volume and improve sorption efficiency, although excessive treatment may lead to structural degradation and loss of carbon yield [132].

Overall, regeneration of vitiviniculture-derived biochars should be optimized to balance pore restoration and functional group recovery while preserving the integrity of the carbon matrix, ensuring sustainable reuse in environmental and agricultural applications.

3.3. Sustainability: LCA and Techno-Economic Analysis

In order for biochar to be a competitive industrial sorbent, it must demonstrate strong reusability and recyclability, thereby reducing operational costs through repeated sorption–desorption cycles. To evaluate this and more aspects, Life Cycle Assessment (LCA), a method which quantifies environmental impacts across all stages of a product's life cycle, and technoeconomic analysis, are essential for assessing the sustainability of biochar applications (ISO 14040:2006) [133]. Recent studies have focused on the sustainability of biochar with LCA method. Sabando-Fraile et al., implemented the LCA method on two optimized sorption scenarios for biochar produced from vine shoot and vine stems. Their results showed that the optimized scenario O1 (minimizing biosorbent dose and stirring time) generally reduced environmental impacts across most categories compared to O2 (efficiency maximizing scenario), with vine shoots performing better than grape stems overall, highlighting how careful adjustment of sorption parameters can significantly lower life-cycle burdens [134]. Similarly, Kaffe compared the biochar production of grape pomace and brewer's spent grain with LCA and reported that biochar from grape pomace significantly outperforms brewer's spent grain, reducing ecosystem damage by 81.4%, global warming potential by 76.5%, and lowering both human health impacts and resource depletion [135].

On the other hand, focusing on the techno-economic dimension, Jin et al. adopted a holistic biorefinery approach for grape pomace, demonstrating that a process integrating grape seed oil, polyphenol, and biochar production achieved exceptional economic per-

formance. More specifically, it exhibited a net present value of 111.7 million US\$, an internal rate of return (IRR) of 34.3%, and a payback period of just 2.5 years, underscoring product diversity and feedstock valorization are key drivers of economic feasibility [136].

Combining both LCA and techno-economic analysis provides a comprehensive and integrated assessment of the overall sustainability and economic viability of biomass valorization pathways, enabling direct comparisons between biochars and feedstock materials. In a study done by Goldaraz et al., in which they compared the LCA of biochar from grape waste (GWB) and sewage-sludge (SSB), GWB demonstrated markedly superior environmental performance, exhibiting roughly 30% lower environmental impact than SSB across most categories. In the same study, Life Cycle Costing was also conducted, in which GWB production exhibited a stronger economic performance than SSB, delivering higher annual profits (253,581 € vs. 164,000 €), greater unit profits (0.94 €/kg vs. 0.82 €/kg for biochar, 0.12 €/m³ vs. 0.11 €/m³ for syngas), and achieving the break-even point with 27% less biochar (24,517 vs. 33,733 kg) and nearly half the syngas output (116,456 vs. 63,082 m³) [137]. With a similar focus in their study, J. S. Ramos & Ferreira highlighted that olive pomace and grape pomace have similar fuel properties, and that gasification and pyrolysis represent the most sustainable options, with environmental impacts reduced to 69.45% and 40.97% of combustion and payback periods under 4 years. Moreover, heat-recovery systems can further decrease impacts by up to 36.70%, highlighting drying as a critical constraint and confirming these technologies as the most sustainable valorization methods [138]. Finally, Agraso-Otero et al. demonstrated that, although the base-case design of a grape-waste biorefinery is constrained by high impacts and capital costs, optimized scenarios aligning with realistic construction and operating values can raise the IRR to 36.16%, underscoring the strong economic potential of this valorization pathway when supported by improved process efficiency and cleaner energy inputs [139].

It is also important to mention that although the sustainability potential is frequently emphasized, it is rarely substantiated through standardized Life Cycle Assessments (ISO 14040/44) [140] and comprehensive techno-economic analyses comparing grape waste valorization pathways with conventional waste management practices and commercial sorbents [141].

4. Discussion

From Section 3, it becomes evident that, while numerous studies have demonstrated the effectiveness of grape waste-derived biochars for various applications, including contaminant removal and environmental remediation, significant differences exist in terms of production methods, modification strategies, sorption performance, economic feasibility, and environmental sustainability [78,82,83,94,96,97,102].

The primary advantage of grape waste-derived biochars lies in their ability to simultaneously address waste management challenges associated with the vitiviniculture industry and generate value-added products [130]. Large quantities of grape pomace, stalks, seeds, and pruning residues are produced annually worldwide, making them attractive and readily available feedstocks for biochar production. For that reason, their conversion into functional sorbents contributes to resource recovery and supports circular economy principles [142,143]. Compared with many other agricultural residues, grape-derived biomass contains significant amounts of lignocellulosic components and mineral constituents that can promote the development of porous carbon structures and active sorption sites following thermochemical treatment [142,144]. Several studies have demonstrated that grape waste-derived biochars exhibit favorable physicochemical properties, including well-developed pore networks, abundant oxygen-containing functional groups, and good sorption performance toward both organic and inorganic contaminants [75–77,82,84].

Furthermore, various physical and chemical modification methods have been shown to improve surface area, pore structure, and surface functionality, leading to enhanced sorption capacities for a wide range of pollutants [94–97,99]. Chemical activation using agents such as KOH, H₃PO₄, and ZnCl₂ has frequently resulted in substantial increases in surface area and pore development compared with non-activated biochars [89,99,101]. However, the selection of modification strategies often involves important trade-offs. Chemical activation generally produces materials with superior sorption performance but may increase production costs, chemical consumption, and secondary waste generation [93,94,105–107]. In contrast, physical activation is often considered more environmentally benign, although it may result in lower surface development and reduced adsorption efficiency [87,98]. Therefore, the choice of modification approach should be guided not only by sorption performance but also by economic and environmental considerations.

A major limitation identified across the literature is the considerable variability in feedstock characteristics and operational parameters. Differences in grape residue type (e.g., pomace, seeds, stalks, or pruning wastes), biomass composition, pyrolysis temperature, heating rate, residence time, and activation protocols can substantially influence the physicochemical properties of the resulting materials [53,145]. As previously mentioned, pyrolysis temperature has been shown to strongly affect aromaticity, stability, pore development, and surface chemistry. While higher temperatures generally increase surface area and porosity, they may simultaneously reduce the abundance of oxygen-containing functional groups that contribute to specific sorption mechanisms [53]. Consequently, direct comparisons between studies remain challenging, and the lack of standardized methodologies limits reproducibility and broader technological assessment [12]. In addition, many investigations are conducted under controlled laboratory conditions using model pollutants, whereas fewer studies evaluate performance in complex real wastewater systems where competing contaminants and fluctuating operating conditions may affect sorption.

From a practical perspective, the scalability of biochar production and application remains a critical challenge. Although laboratory-scale results are generally promising, large-scale deployment requires consideration of feedstock availability, process energy demand, activation costs, regeneration efficiency, and overall environmental impacts. The seasonal nature of grape waste generation may also influence feedstock logistics and storage requirements. The balance between maximizing sorption performance and maintaining economic and environmental sustainability represents a key consideration for industrial adoption [146]. Furthermore, the long-term stability and reuse potential of modified biochars remain insufficiently explored, highlighting the need for more comprehensive assessments of operational durability and lifecycle performance. Techno-economic analyses and full-scale demonstrations remain scarce compared with the large number of laboratory studies currently available [147].

Overall, the reviewed studies confirm the considerable potential of grape waste-derived biochars as sustainable remediation materials. Their abundance (even though seasonal), low cost, favorable physicochemical properties, and compatibility with circular bioeconomy strategies make them particularly attractive alternatives to conventional adsorbents [83]. Nevertheless, their successful transition from laboratory-scale demonstrations to practical applications will depend on overcoming challenges related to process optimization, methodological standardization, economic feasibility, and scale-up [148,149]. In this context, the potential utilization of grape distillation by-products as biochar modifying agents represents an unexplored yet promising research avenue that could further enhance resource valorization, reduce overall cost and promote circularity within the vitiviniculture sector.

5. Conclusions

In conclusion, the valorization of by-products derived from viticulture, winemaking, and distillation processes presents a promising way for sustainable waste management and resource recovery. Among the various valorization strategies, the production of biochar from these lignocellulosic residues stands out due to its environmental benefits and versatile applications. To further enhance biochar's physicochemical properties, a variety of activation methods, ranging from physical to chemical treatments, were studied, demonstrating biochar's usability in more fields with enhanced efficiency. Thus, the utilization of these by-products not only reduces environmental pollution but also creates added economic value within the viticulture and spirits industries, fostering a circular bioeconomy. To that end, closing the loop with biochar regeneration is crucial, not only to mitigate secondary environmental risks, but also to demonstrate the strong reusability and recyclability of biochar compared to other sorbent materials. Moreover, it is evident that the future utilization of biochar from grape waste can be further supported by technoeconomic and life cycle analyses, which carve the pathways to mitigate environmental impact of their use and production, as well as the technoeconomic aspects of their use on a larger scale.

Looking ahead, another compelling future research direction involves the integrated utilization of distillation liquid by-products as activating agents for biochar produced from viticulture and winemaking residues. These liquid fractions, distillation heads and tails fractions, rich in alcohols, esters and organic acids, offer a sustainable and cost-effective alternative to conventional chemical activators, potentially enhancing biochar's surface chemistry and adsorption capacity. This novel approach could synergistically close the loop within the production chain, promoting zero-waste practices and elevating the functional performance of biochar-based materials. Advancing this concept through further future research and scale-up will be crucial to unlocking its full potential in environmental and agricultural applications.

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Abbreviations

The following abbreviations are used in this manuscript:

5-HMF	5-Hydroxymethylfurfural
AZ	Azithromycin
BC	Biochar
BOD	Biochemical Oxygen Demand
CEC	Cation Exchange Capacity
COD	Chemical Oxygen Demand
CPX	Ciprofloxacin

DES	Deep Eutectic Solvents
DMSO	Dimethyl Sulfoxide
E-bSU	Carbon-Paste Electrode
EC	Electric Conductivity
Ef.	Efficiency
GWB	Grape Waste Biochar
HTC	Hydrothermal Carbonization
IRR	Internal Rate of Return
LCA	Life Cycle Analysis
LOD	Limit Of Detection
LOQ	Limit Of Quantification
MB	Methylene Blue
OP	Orange Peel
PAHs	Polycyclic Aromatic Hydrocarbons
PLA	Polylactic Acid
PM	Particulate Matter
SGP	Spent Grape Pomace
SMX	Sulfamethoxazole
SSA	Special Surface Area
SSB	Sewage Sludge Biochar
TC	Tetracycline
TMP	Trimethoprim
VOCs	Volatile Organic Compounds

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