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Review

Sustainable Technological Applications of Green Carbon Materials

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Abstract: Green carbon-based materials (GCM), i.e., carbon materials produced using renewable biomass or recycled waste, ought to be used to make processes sustainable and carbon-neutral. Carbon nanomaterials, like carbon dots and the nanobichar families, and carbon materials, like activated carbon and biochar substances, are sustainable materials with great potential to be used in different technological applications. In this review, the following four applications were selected, and the works published in the last two years (since 2022) were critically reviewed: agriculture, water treatment, energy management, and carbon dioxide reduction and sequestration. GCM improved the performance of the technological applications under revision and played an important role in the sustainability of the processes, contributing to the mitigation of climate change, by reducing emissions and increasing the sequestration of CO_2eq.

Keywords: green carbon nanomaterials; green carbonaceous materials; biomass; waste; biochar; nanobiochar; sustainability

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1. Introduction

Green nanomaterials/materials are being proposed to mitigate sustainability problems associated with using natural resources and/or production processes [1–19]. To reduce the environmental impacts related to natural resources and toxicity, carbon-based nanomaterials and/or carbonaceous carbon are being suggested as alternatives, together with the utilization of renewable biomass as a carbon source, and named green carbon nanomaterials (GCN) and/or green carbonous materials (GCM) [7–12]. Moreover, environmentally friendly synthetic processes are being considered to produce these green products [6].

GCN/GCM appear as sustainable alternatives for several applications: agriculture [12–18], water treatment [1], sensors [2,7], biomedical applications [4,10,11], and carbon dioxide sequestration [12–18]. GCNs are usually synthesized by hydrothermal methods directly from the powered carbon source or, when a specific functionality requires improved performance, by mixing with specific reagents (Figure 1). For example, carbon nanomaterials obtained directly from biomass usually have a low quantum yield (QY). However, mixing with citric acid and a nitrogen source increases the QY to 61%, which is more suitable for chemical/biochemical sensor research [19].

GCM can be produced as a by-product of GCN synthesis or by the direct carbonization or pyrolysis of the biomass. For example, biomass as a raw material for GCN production originated from an insoluble activated carbon material, besides the soluble nanomaterial, with a large specific surface area of about 295 m^2/g [20]. Biochar is a typical GCM obtained directly from renewable biomass or waste and is produced by heating at high temperatures without oxygen (for example, in the presence of nitrogen and/or carbon dioxide), followed by a final physical–chemical transformation for functionality tuning (Figure 2) [15].

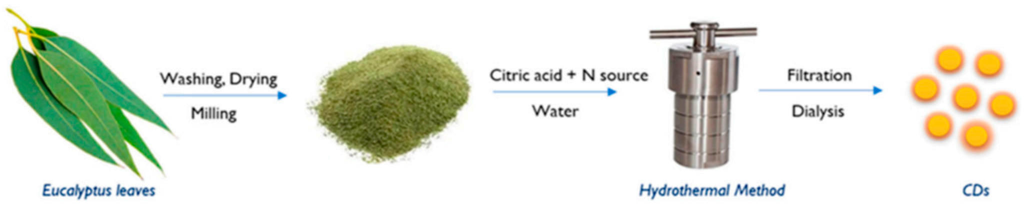

Figure 1. Typical scheme of carbon-based nanomaterial preparation from eucalyptus leaves. Adapted from reference [19].

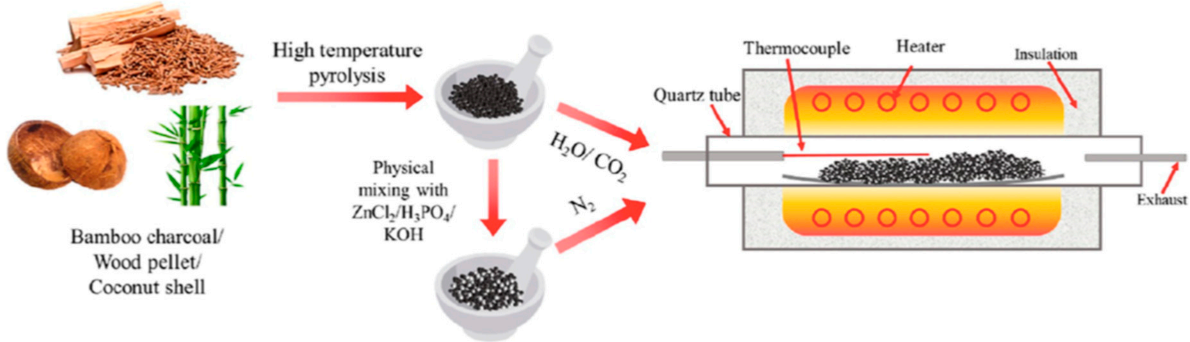

Figure 2. Schematic representation of biomass pyrolysis and biochar activation processes [15]. Copyright (2023) from the American Chemical Society.

According to their origin/characteristics and/or synthesis methodology, GCN/GCM have different general designations. If GCN have no well-defined structure, they are called carbon dots (CD), carbon quantum dots (CQD), or nanobiochar, and if they have a well-defined structure, they fall within the classical carbon nanomaterials, like graphene oxide (GO) and carbon nanotubes (CNT). CD and CQD usually refer to the same carbon nanomaterial, which is synthesized by bottom-up or top-down technologies [21], while nanobiochar is obtained from bulk biochar through top-down methodologies, like ball milling, centrifugation, and sonication [22]. The most common CGM are biochar and activated carbon (AC).

To promote the sustainability of technological nano/bulk materials, raw materials must be obtained from renewable sources or waste recycling. Regarding carbon-based nanomaterials/materials, straightforward sources of raw materials are renewable biomass and anthropogenic/technological waste. The use of these sustainable advanced products in critical technology processes, replacing high-environmental-impact components, is a fundamental approach toward the global sustainability of our society. Four typical critical processes are currently under heavy sustainability discussion:

(i) agricultural food production and the classical industrial strategies to increase yield production, usually based on unsustainable agricultural practices;
(ii) technological strategies to treat water, either fresh or wastewater, which usually involve energy and/or the use of nonrenewable natural resources;
(iii) batteries for electric equipment that require highly unsustainable mineral resources;
(iv) technologies for carbon dioxide sequestration to mitigate climate change.

These themes contribute significantly to the following United Nations Sustainable Development Goals (SDG): 2—end hunger, achieve food security and improved nutrition, and promote sustainable agriculture; 6—ensure availability and sustainable management of water and sanitation for all; 7—ensure access to affordable, reliable, sustainable, and modern energy for all; 9—build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation; 12—ensure sustainable consumption and production patterns; 13—take urgent action to combat climate change and its impacts; and 15—protect, restore, and promote the sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.

GCN/GCM are being proposed to be incorporated into these critical processes to replace other unsustainable materials. This review considers carbon nanomaterials synthesized from renewable carbon residuals in the last two years (since 2022), ensuring their intrinsic sustainability in these processes.

2. Agriculture Applications

2.1. Carbon-Based Nanomaterials

Traditional agricultural NPK inorganic fertilization markedly contributes to the carbon footprints of products, contributing negatively to the sustainability of agricultural farms. Carbon nanomaterials are being proposed as potentially more sustainable agents to be used in agricultural practices [20,23]. Although there is no common effect on all plants exerted by carbon nanomaterials, an increasing trend in production yields is observed (Figure 3) [20]. However, most of the research work in this area has been done with well-characterized carbon nanomaterials like graphene oxide (GO), carbon nanotubes (CNT), and fullerenes, among others [20,23], which are not synthesized from renewable biomass, and sustainability is compromised.

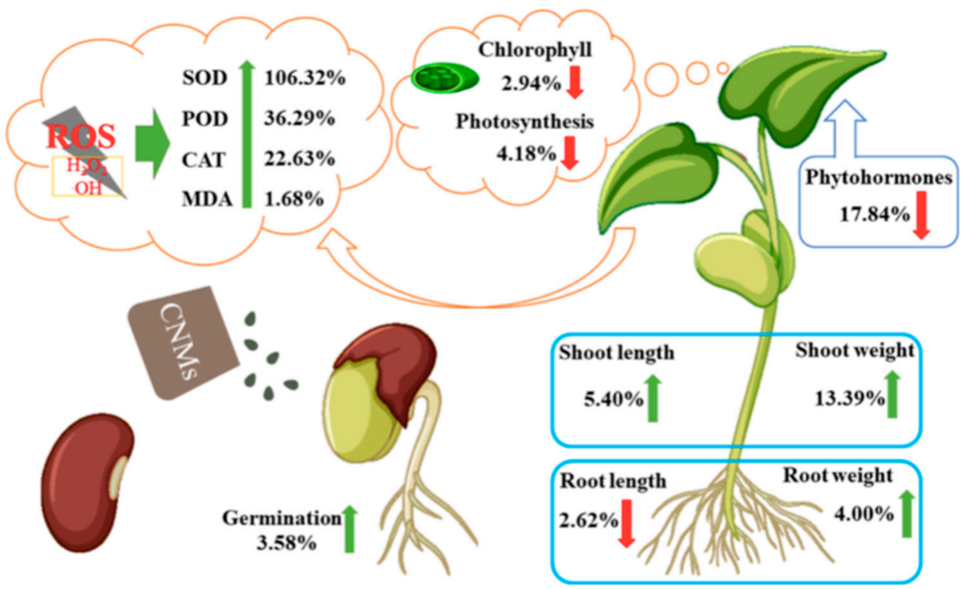

Figure 3. The effect of carbon-based nanomaterials on plants [20]. Copyright (2023) from the American Chemical Society.

Nitrogen-doped carbon dots (N-CD) were synthesized from fresh betle leaves (*Piper betle*) [24]. Namely, 5 g of betle leaves, finely cut into pieces, were mixed with 60 mL of water and kept at 180 °C for 10 h, and an N-CD solution was obtained after the centrifugation and filtration of the solution through a 0.22 µm filter. The average size of the carbon nanoparticles was 3.2 nm. The filtrated solution (1.9 mg/L) was used to irrigate strawberries, and the results were compared with those of strawberries irrigated with water and regular nutrients. The N-CD had a marked positive impact on strawberry production compared to the two control experiments (Figure 4). The nanoparticles' water solubility and nanometer size allowed their assimilation by the strawberries' roots and increased the chlorophyll, phenol, and carbohydrate content [24].

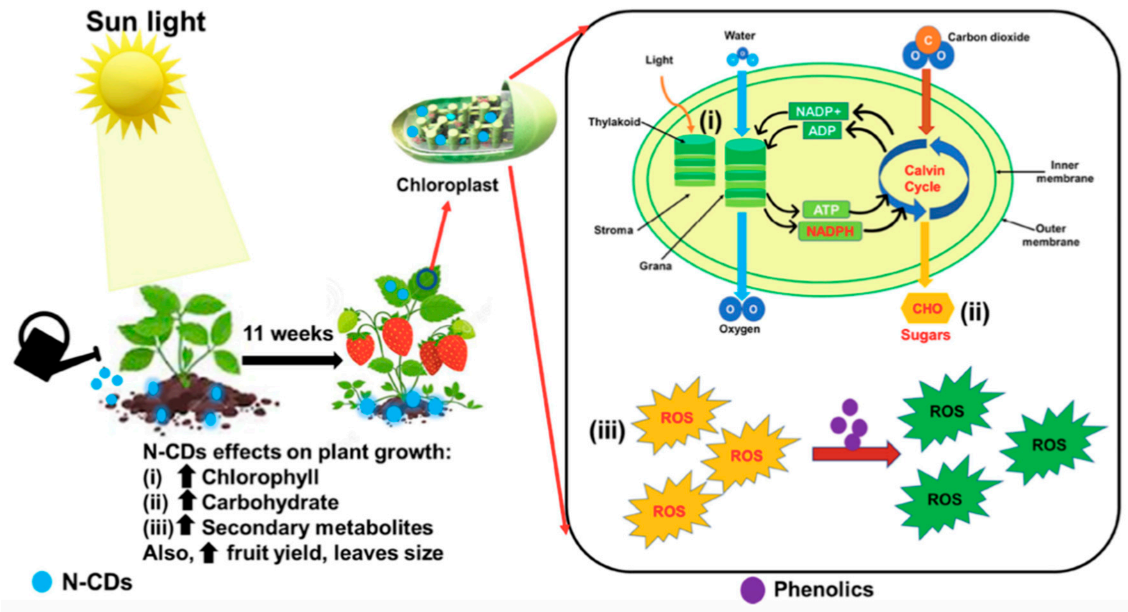

Figure 4. Proposed mechanism of CD effects on strawberries [24]. Copyright (2023) from the American Chemical Society.

Carbon dots produced from sugar beet molasses (a byproduct of sugar factories) (M-CD) were assayed to alleviate the effects of drought and salt stress on tobacco plant growth [25]. M-CD were obtained directly from the supernatant of the centrifugation of a mixture of 5 g of molasses and 10 mL of water [25]. The effect of the increasing M-CD concentration solutions on the tobacco plant was observed by replacing the irrigation water with the M-CD solution. When the carbon nanomaterials were present, the tobacco plant was more resilient under salt and drought stresses [25].

Carbon-based nanomaterials can also be applied to the materials used in greenhouse coverings. Carbon quantum dots (CQD) from agave fiber bagasse (obtained from a tequila distillery) were synthesized by burning them in an open-air powder (sieved with a 200 mesh) at 500 °C for between 0.5 and 2 h [26]. The CQD were obtained by the filtration (through a 0.22 μm filter) of the suspension resulting from the mixture of the treated powder with water and after sonication and centrifugation. The CQDs' quantum yield (QY) varied from 9.17 to 15.74 depending on the combustion time—the longer the combustion time, the higher the QY. The average size of the carbon nanoparticles in the 0.5 h combustion time sample was 5.6 nm ± 1.2 nm [26]. Because the purification procedure of the CQD sample under analysis in this work was only based on filtration through a 0.22 μm filter, the nanoparticles' preparation was expected to be contaminated with molecular substances resulting from the combustion process. These CQD were applied on acrylic sheets, resulting in a coating used in a greenhouse experiment [26]. The CQD coating filtered the sunlight with a two-fold benefit on plants: (i) they absorbed harmful solar photons and (ii) they converted higher-energy photons into lower-energy blue radiation that matched the absorption of chlorophyll a. The plants (ipomoea) under this CQD coating had faster germination rates and better plant growth rates [26].

Due to the nanometric size of carbon dots (CD), they enter plants by root and leaf absorption and may interfere with the plant's physiology (Figure 5) [27]. CD will increase the crop yield by enhancing plant photosynthesis, acting as nanofertilizers, promoting good seed germination by facilitating water absorption, improving plants' resistance to abiotic stress, and inactivating toxic pollutants [27].

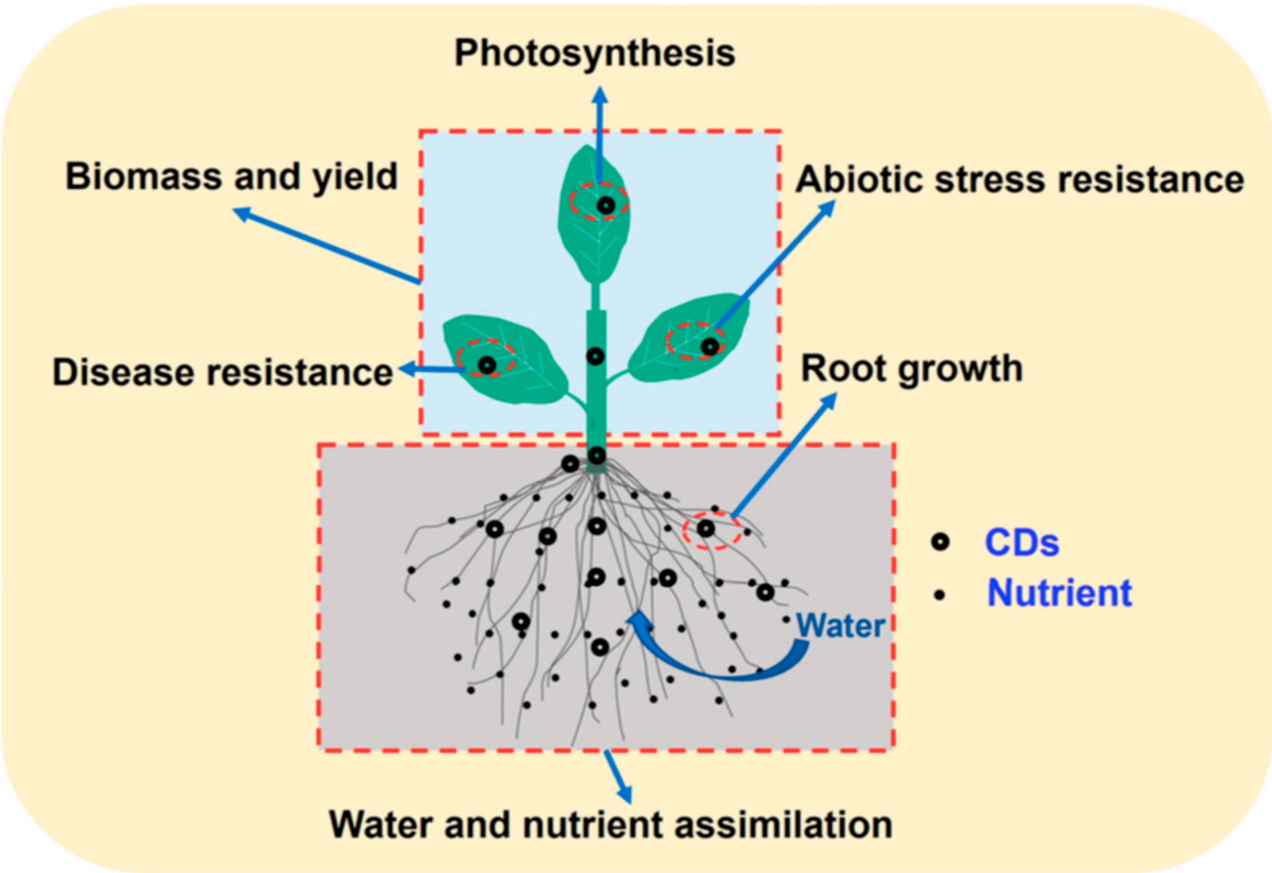

Figure 5. Physiological functions of CD on plants. Adapted from reference [27].

Carbon nanomaterials have another important role in agricultural practices, namely as nanocarriers for pesticides and fertilizers, allowing the controlled release of active molecules [20]. Nevertheless, carbon nanomaterials must have intrinsic sustainability, i.e., being synthesized from renewable raw materials (GCN), and, in the agriculture business, the incorporation of agricultural residuals into the productive cycle is highly encouraged within the ongoing transition to the circular economy.

GCN interfere with the different phenological stages of plants, with potential increases in crop yields. However, these studies are still in the preliminary stages and further information is required about the long-term effects of nanomaterials in general and GCN in particular. Moreover, sustainable production processes of GCN must be designed so as not to negatively affect the carbon footprint of agricultural crop production.

2.2. Carbon-Based Materials—Biochar

Biochar is one of the biomass-based carbon materials that has been highly investigated. Biochar is a product of the valorization of feedstocks, like municipal organic waste and agri-industrial residues, through slow pyrolysis [28–37]. Thermal processes, like pyrolysis and carbonization, convert biomass into a carbon-rich microporous material with a well-developed porous structure, a highly specific surface area, and a high degree of aromatization (Figure 6) [28–31]. These features can be tuned using different raw materials and the technical characteristics of pyrolysis. Biochar is added to soil to modify its physical and chemical composition, microbial activity, soil fertility, and pollution load [28–37].

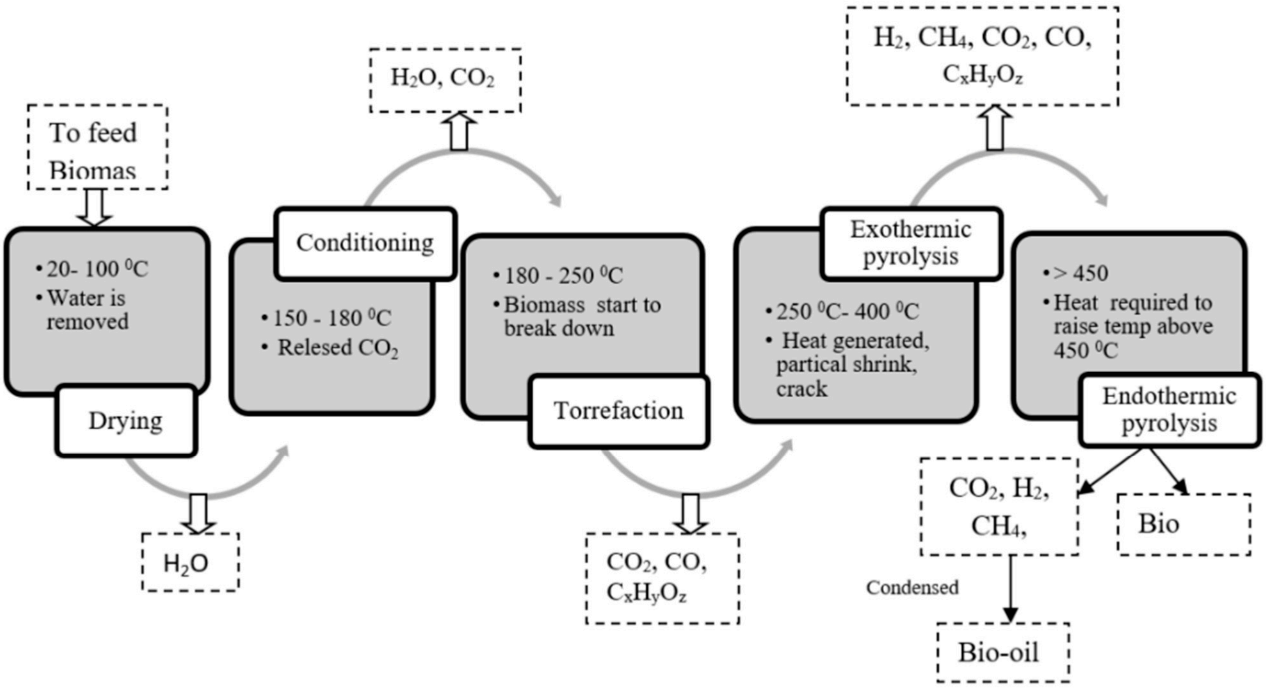

Figure 6. Biochar production process. Adapted from reference [31].

Biochar contains inorganic elements that are macronutrients, particularly N, P, and K, and micronutrients to plants; when added to soils, they will improve their fertility, resulting in high crop yields [28,29]. The bioavailability of the nutrients may not necessarily result from the nutrient load of biochar but from the modifications of the soil's physical properties, like the bulk density, porosity, water retention, and hydraulic conductivity, which result in an increase in the plant's nutrient use efficiency [28,29]. Improvements in soil organic matter (SOM) and the corresponding soil structure (macro- and microaggregates) are observed upon biochar soil incorporation [31]. Biochar can also stimulate the soil's microbial population and its activity, particularly mycorrhizal fungi [28,29]. Another essential property of biochar is its specific surface area (SSA) and the adsorption of organic compounds and metal ions, which can improve the soil quality by immobilizing toxic pollutants [28]. Moreover, biochar can correct the pH in acidic soils and/or improve the cation exchange capacity (CEC) [28,29]. Figure 7 highlights the effects of adding biochar to the soil on its physicochemical properties [29].

However, biochar is not a well-defined chemical substance with constant properties. Indeed, the biochar's characteristics and functional properties depend on the raw materials and on the technical features of the pyrolysis [29]. Some examples demonstrate this variability and the potential to tune the method according to the desirable application [29].

(i) The pyrolysis of hardwood biomass results in a biochar with higher organic carbon. If biochar is produced from animal manure, it results in a higher NPK nutrient load and a higher CEC [28]. Different raw materials produce a nutrient-enriched biochar [32]: seaweed, potassium; manure, phosphorous; rice straw, silicon; bone, calcium; keratin, nitrogen.
(ii) Higher pyrolysis temperatures produce a biochar that raises the nutrient concentrations, soil porosity, SSA, and carbon content and increases the pH [29]. Biochar produced at lower temperatures improves the soil CEC [28].
(iii) A high-temperature biochar produced from lignin-rich feedstocks may decrease the methane and nitrous oxide emissions in acidic soils and contribute to carbon sequestration [30]. A low-temperature biochar from manure is increases the nutrients and improves the crop yields in low-fertility soils [30].

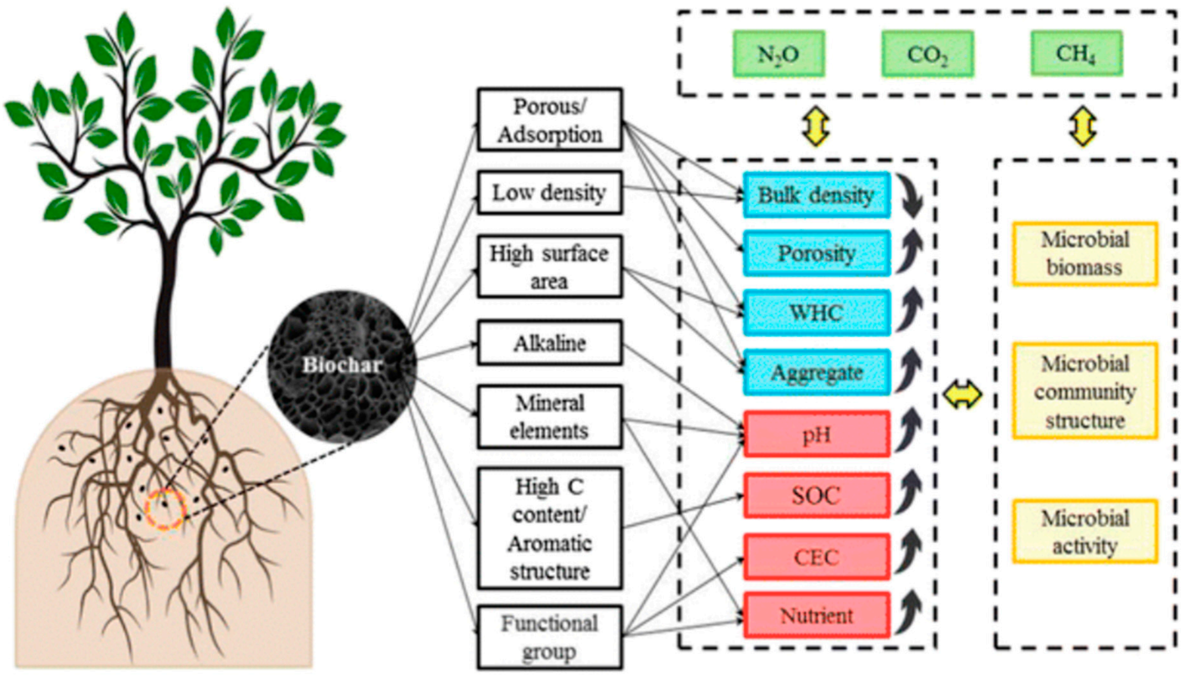

Figure 7. Effect of adding biochar on soil physicochemical properties. Adapted from reference [28].

Biochar has been used as a growing medium in hydroponic cultures [31] and to amend composting processes to reduce greenhouse gas emissions and nitrogen losses [31].

Slow-release fertilizers (SRFs) are a solution to nutrient loss from the soil through leaching, volatilization, denitrification, and surface runoff. Biochar SRFs (BSRFs), derived from agricultural waste, are being proposed as a more sustainable alternative [32–34]. BSRFs are obtained by the co-pyrolysis of biomass with a chemical substance containing the nutrient, such as phosphate rock or urea [32].

In recent years, nanobiochar has been proposed to combine the material's favorable properties with a nanomaterial [38,39]. A study on the foliar spraying of nanobiochar in cauliflower production showed beneficial effects on the crop yields and quality of cauliflower [38]. In a study on corn nutrient uptake from farmyard manure, low concentrations of nanobiochar significantly improved the microbial biomass and increased the macronutrient uptake, indicating a positive impact on the soil microorganisms and their activity [39]. However, when higher concentrations of nanobiochar were used, toxicity was observed [39].

3. Water Treatment

Due to the ubiquitous environmental contamination and the increase in public and regulatory environmental agencies' awareness of water quality, water treatment is becoming more challenging. Carbon nanomaterials are being proposed to incorporate advanced water treatment technologies [40–42]. During the synthesis of GCN, a solid residual is also produced, because GCN are soluble in water and separated from the carbonaceous material, a GCM, by centrifugation [19]. Both GCN and GCM have the potential to be used in environmental remediation technologies.

Carbon dots (CD) synthesized by an eco-friendly hydrothermal approach from brewing waste, spent grains, and spent yeasts were used as photocatalysts for wastewater treatment [43]. Nitrogen-doped CD, with an average size of about 100 nm, were produced by the hydrothermal carbonization (24 h at 200 °C) of the brewing waste, mixed with water or residual beer, and purified by dialysis after centrifugation and isolated as a solid after being freeze-dried. In this work, the carbon nanomaterials presented in the solution were isolated, and the insoluble material was discarded. CD were immobilized in polyvinyl alcohol and assayed for methylene blue (MB) degradation under ultraviolet irradiation

(Figure 8). Promising results were observed for the photodegradation of the dye MB in water samples [43].

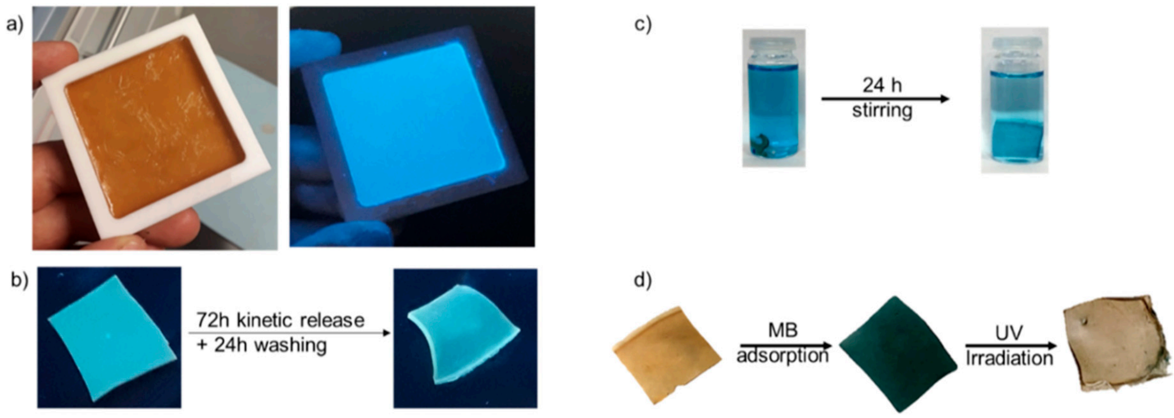

Figure 8. (**a**) PVA-CD hydrogel under visible light and UV light, (**b**) PVA-CD hydrogel fluorescence before and after washing treatment, (**c**) MB absorption test on PVA4 hydrogel, and (**d**) PVA4 hydrogel before and after MB absorption and after 24 h of UV irradiation [43]. Copyright (2022) from the American Chemical Society.

CD synthesized from fresh guava leaves (*Psidium guajava*) were used to clean up oil spills [44]. CD, with a size of 2.42 ± 1.1 nm, were produced using the following process: 50 mL of ethanol was mixed with 10 g of powder leaves and heated at 70 °C for 2 h; after filtration, the solution was carbonized using a 600 W microwave for 5 min; the obtained solid sample was washed with water and dried at 60 °C for future use. An ethanol suspension of the CD (1.5 mL of 33.32 mg/mL) was added to a 200 mg cotton piece and left to dry at room temperature. The CD-coated cotton was used for the cleanup of oil spills [44] (Figure 9).

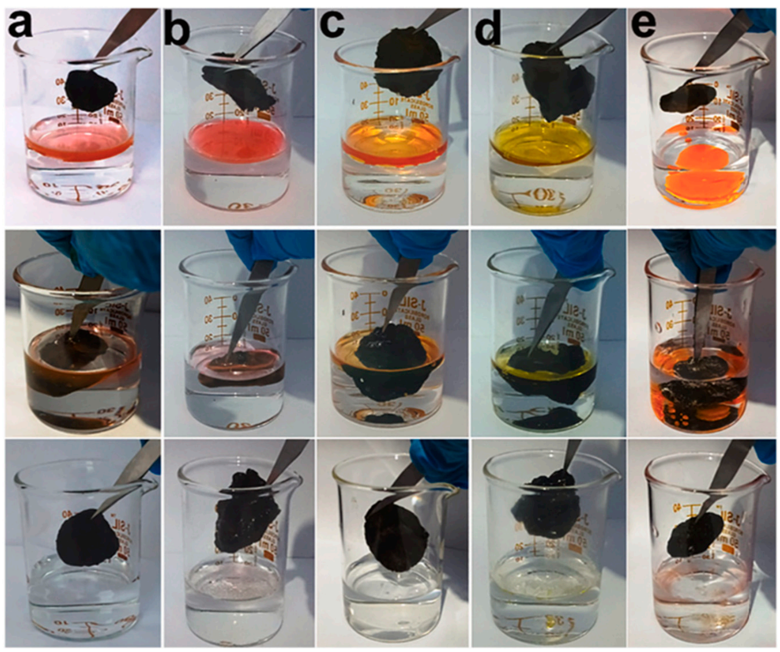

Figure 9. Cleanup of light and heavy oils ((**a**) silicon oil, (**b**) refined oil, (**c**) motor oil, (**d**) mustard oil, and (**e**) carbon tetrachloride) from an oil–water mixture by CD-coated cotton at room temperature. For better visualization, Nile red dye was added to the silicon oil, refined oil, and carbon tetrachloride [44]. Copyright (2022) Elsevier Ltd.

Green carbon quantum dots (G-CQD) were prepared from extracts of fresh guava leaves (*Psidium guajava*) by a hydrothermal process at 200 °C for 5 h [45]. Purified powdered G-CQD were obtained by lyophilization after centrifugation and filtration using a 0.22 mm filter. The G-CQD had a normal size of 1.27 nm and a quantum yield of 32%. The effect of the G-CQD in the catalysis of the degradation of two dyes, bromophenol blue and Congo red, in the presence of $NaBH_4$, was analyzed, and the color of the solutions was removed after 30 min [45]. A carbon nanomaterial (with a size in the range of 63 to 137 nm) was synthesized from a *Spirulina platensis* aqueous solution (a 100 mg/mL solution was centrifuged and diluted 1:5 with water) by the following method:

(i) the solution was processed by microwave-assisted technology (800 W for 60 min);
(ii) centrifugation was performed to remove the precipitated material, followed by 1:1 dilution with water and by secondary processing with a microwave oven for 30 min at 800 W;
(iii) centrifugation was performed to obtain the nanomaterial solution.

The effect of the obtained solution on the photocatalytic discoloration of aqueous solutions of Reactive Red M8B dye was studied by keeping them under sunlight (~40,000 lx and without any agitation. Dye degradation of 95.5% was achieved after 6 h, following first-order kinetics. The degradation of the dye into smaller, easily degraded molecules was confirmed by GC-MS [46]. In another study with this carbon nanomaterial produced from *Spirulina platensis*, 90–97% of textile effluents were successfully photodegraded using a 1 mg/mL concentration [47].

Activated carbon (AC) is a standard, well-known material commonly used in water/wastewater treatment stations. AC can be produced from biomass (Figure 10) [48]. AC is used in the adsorption of organic pollutants (dyes, pesticides, phenols, pharmaceuticals, etc.) and toxic heavy metals present in raw water to be distributed for human consumption or in the treatment of industrial effluents [48].

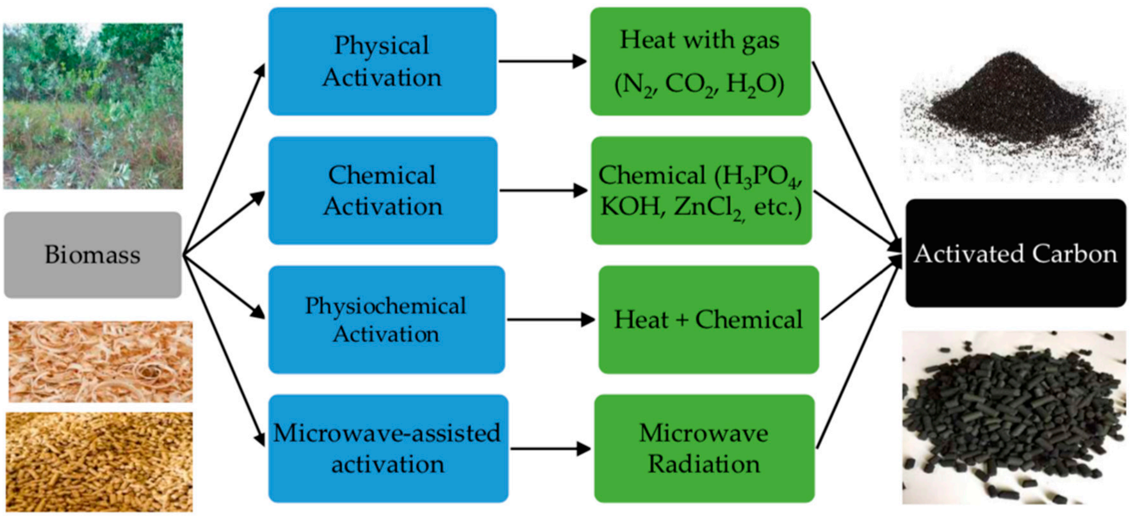

Figure 10. Technologies for activated carbon preparation from biomass. Adapted from reference [48].

Another emerging area of research is the use of renewable biomass to produce GCN to be used in water disinfection as an alternative to chlorine and to minimize disinfection byproduct generation. Carbon dots (CD) were prepared from coconut waste by hydrothermal carbonization and pyrolysis, followed by sonication, and doped with urea, polyethyleneimine (PEI), and hexamethylenetetramine (HMTA), which resulted in enhanced antibacterial properties [49]. These CD were infused in chitosan beads and assayed in the disinfection of water contaminated with *Escherichia coli*, reducing the colonies from 5.41×10^2 CFU/mL (control group) to 2.16×10^2 CFU/mL [49].

GCN synthesized by microwaves are being proposed in water treatment applications [50]. The use of microwave reactors adds more sustainability to the carbon-based materials because fast reactions, and consequently smaller energy requirements, are needed in their synthesis. Coupling biomass raw materials with microwave technology results in top-dawn synthesis methodologies involving the breakdown of carbonaceous materials and does not emit carbon dioxide or methane, as observed when simple synthetic chemical substances are used as raw materials [50]. The synthesized GCN are mainly used in environmental treatment as adsorbents for chemical pollutants [50].

Biochar-type materials were prepared from the pyrolysis (700 °C, retention time of 2.5 h, and heating rate of 5 °C/min under nitrogen) of corn stover [51]. This carbon-based material was used to remove cadmium (II) ions from water, with a maximum adsorption capacity of 13.4 mg/g [51]. Biochar has been used to remove heavy metals from aqueous solutions due to its large SSA and the precipitation of metal hydroxides due to the high pH and surface O/C ratio and polarity [52].

Although biochar research in agriculture is a well-established area, its nanosized fraction, nanobiochar, is in the early stage of scientific research. Nanobiochar is being proposed for environmental remediation, although the mechanism of action is poorly understood [53–56]. Nanobiochar has superior physicochemical properties to biochar, such as high catalytic activity, a large SSA, and high environmental mobility [53]. The main applications of nanobiochar in environmental treatment technologies are in pollutant removal, like heavy metals, toxic organic substances, and emerging pollutants, via adsorption mechanisms like ion exchange, complexation, precipitation, electrostatic interaction, and physical adsorption [53–55]. As discussed above, the biochar's structure and properties depend on the raw materials and technological characteristics of the pyrolysis process, and the same is naturally observed for nanobiochar [54,55]. Temperature is a critical factor for nanobiochar's functionality; for example, the SSA, ash content, and carbon content increase with the pyrolysis temperature, although this effect depends on the raw material [56]. Nanobiochar produced with a lower pyrolysis temperature resulted in abundant surface functional groups, high absolute zeta potential, and strong suspension stability [56]. Nevertheless, the properties of nanobiochar, like those of biochar, are dependent on the raw material, and each product must be assayed and its properties tuned for the specific type of application.

Nanobiochar enhanced with magnetic properties has been proposed for technological applications [54]. It is prepared by ball milling biochar produced from biomass mixed with an inorganic magnetic precursor. In water treatment, it is being assessed for the adsorption of toxic heavy metals and pharmaceutical water pollutants [54].

GCM/GCN can contribute to the treatment of water under three basic mechanisms: the adsorption of pollutants, the disinfection of pathogenic microorganisms, and the degradation of chemical pollutants. The treatments based on the adsorption of chemical pollutants are questionable from the point of view of sustainability because the pollution is being transferred to another location, where it should be eliminated or safely deposited.

4. Energy Management

In the context of the present energy transition towards renewable energy resources, the challenges of electrical energy management, i.e., sustainable generation and high-performance energy storage systems, are enormous. Sustainable electronic devices and accessories, such as supercapacitors, are necessary to manage the expected renewable electric energy production [48]. Electrodes, usually made from carbon-based materials, are critical components of these electronic devices. Besides activated carbon (AC), carbon nanomaterials (CNTs and graphene) have an important role in energy conversion and storage [48].

Corn leaf waste was carbonized in a temperature range between 400 and 600 °C (heating period of 5 °C/min with a dwell period of 2 h) to obtain biocarbon [57] (Figure 11). The 600 °C biocarbon was ball-milled for 2 h at 250 rpm, followed by treatment with hydrochloric acid for 30 min at 50 °C (sample C600B). The ball-milling and washing treatments generated particles smaller than 20 µm and with fewer impurities. This biocarbon sample was used to assemble electrodes as an anode material for Na-ion batteries, using carboxymethyl cellulose as a binder [57]. The electrochemical performance of the C600B sample was represented by a capacity of 171 mAh g^{-1} after 10 cycles at 100 mA g^{-1}; the Na-ion storage capacity was 134 mAh g^{-1} after 100 cycles; and the charge-transfer resistance and Na-ion diffusion coefficient were, respectively, 49 Ω and 4.8 × 10^{-19} cm^2 s^{-1} [57].

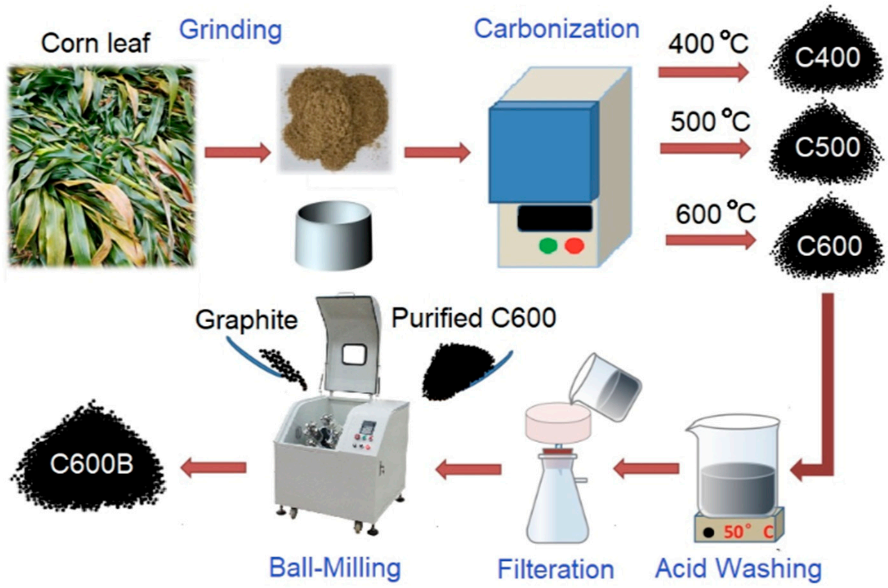

Figure 11. Scheme of carbon material preparation from corn leaf. Adapted from reference [18].

Research in carbon nanoparticles to be used in high-performance rechargeable batteries is increasing due to their supreme conductivity values and excellent mechanical stability [58]. Indeed, increasing their storage capacity, particularly the gravimetric capacitance, cyclic stability, and densities (energy and power), is necessary for the next generation of sustainable supercapacitors [58].

5. CO_2 Reduction and Sequestration

The ongoing climate changes due to the increased atmospheric concentrations of greenhouse gases (GHG) have justified the current carbon neutrality objectives defined in the COP's regular meetings and by regional or country-specific regulations. By the middle of the current century, the emissions of carbon dioxide equivalents must be neutralized by the same amount that is sequestered. The current situation is observed because the economy is heavily based on the carbon cycle, stimulated by the use of fossil fuels, and the contribution of carbon-based materials to the mitigation of this problem requires increased GHG sequestration.

Carbon quantum dots (CQD) were obtained from macaúba (*Acrocomia aculeate*) fibers by mixing 1 g with 20 mL of 1 M sodium hydroxide and heating the mixture to 200 °C for 18 h [59]. CQD were purified by centrifugation followed by dialysis (MWCO of 3500) for a week and lyophilized to obtain a powder with a 28% yield. The CQD had an average size of 1.9 ± 0.8 nm. These CQD catalyzed the reduction of CO_2 into CH_4 in water with an evolution rate of 99.8 nmol/g at 436 nm [59].

One of the technologies used for CO_2 capture is its sequestration in a solvent; the most well known is monoethanolamine (MEA). Activated carbon (AC) has shown strong potential to replace MEA as an adsorbent for CO_2 [48]. With a production temperature of 1073 °C and KOH as the activation agent, AC from Paulownia sawdust exhibited a CO_2 adsorption capacity of 7.14 mmol/g at 273 K [48]. The production of AC with surface amino functional groups and a large surface area improves the CO_2 sequestration potential [48].

Biochar, a persistent form of solid carbon produced from biomass at high temperatures under reduced oxygen conditions, is considered a carbon dioxide removal technology that can be deployed at scale [13–18,59–61]. Indeed, a net emission reduction in the range of 0.4–1.2 Mg CO_2 equivalents per Mg of dry feedstock, through carbon persistence, avoided non-CO_2 emissions and decreased native soil organic carbon mineralization [13,18]. Considering the current carbon neutrality objectives, within the climate change objectives and/or regulations, biochar production from crop residues may constitute significant net CO_2 avoidable emissions with the potential for carbon sequestration (Figure 12) [13].

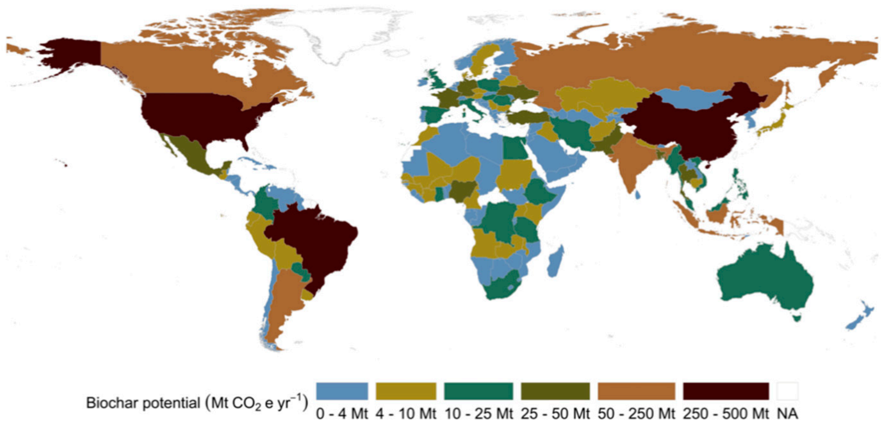

Figure 12. Global biochar carbon dioxide removal potential map (Mt CO_2e $year^{-1}$). Adapted from reference [13].

Biochar, like AC, as discussed previously, can also be directly involved in technological CO_2 capture processes [14–16]. However, biochar's intrinsic CO_2 sequestration potential is low, and, like AC, it needs to be activated in order to become an alternative to current capture technologies. CO_2 capture by biochar, mainly by a physical adsorption mechanism, is mainly determined by the existence of micropores that must be activated [15]. Physical activation can be achieved by mixing the reacting biomass with CO_2 and/or H_2O during the biochar's production, and chemical activation is achieved by reaction with strong bases, acids, and molten salts [14–16]. Moreover, considering the acid properties of CO_2, surface functionalization with alkaline amine groups would optimize the CO_2 capture potential [15].

The concept of climate-smart agriculture originated from the carbon neutrality objectives to be accomplished by the middle of the current century [29]. Biochar's impact on the percentage of soil organic carbon (SOC), methane and nitrous oxide emissions, and crop yields is being assessed regarding agricultural practices [29,60,61]. For example, biochar application in China's farmlands increased the SOC by 1.9 Pg C and reduced the CH_4 and N_2O emissions by 25 and 20 Mt CO_2 eq./year, respectively [29].

Biochar is produced under an inert atmosphere to inhibit the oxygen oxidation of the organic matter—for example, nitrogen—by thermal treatment at high temperatures. However, if carbon dioxide is used instead of an inert gas and the biochar is produced by slow pyrolysis, further positive features can be obtained [17]. Indeed, the use of CO_2 corresponds to its capture, and the lifecycle assessment of the produced biochar indicates an improved carbon footprint, contributing to the mitigation of global warming. Moreover, the properties of this biochar become different from the properties of those produced under an inert atmosphere, and the differences depend on the temperature used in the synthesis process, as is indicated in Figure 13 [17]. Briefly, the biochar produced under CO_2 has improved characteristics, such as SSA, porosity, elemental composition, and surface-active chemical functional groups [17].

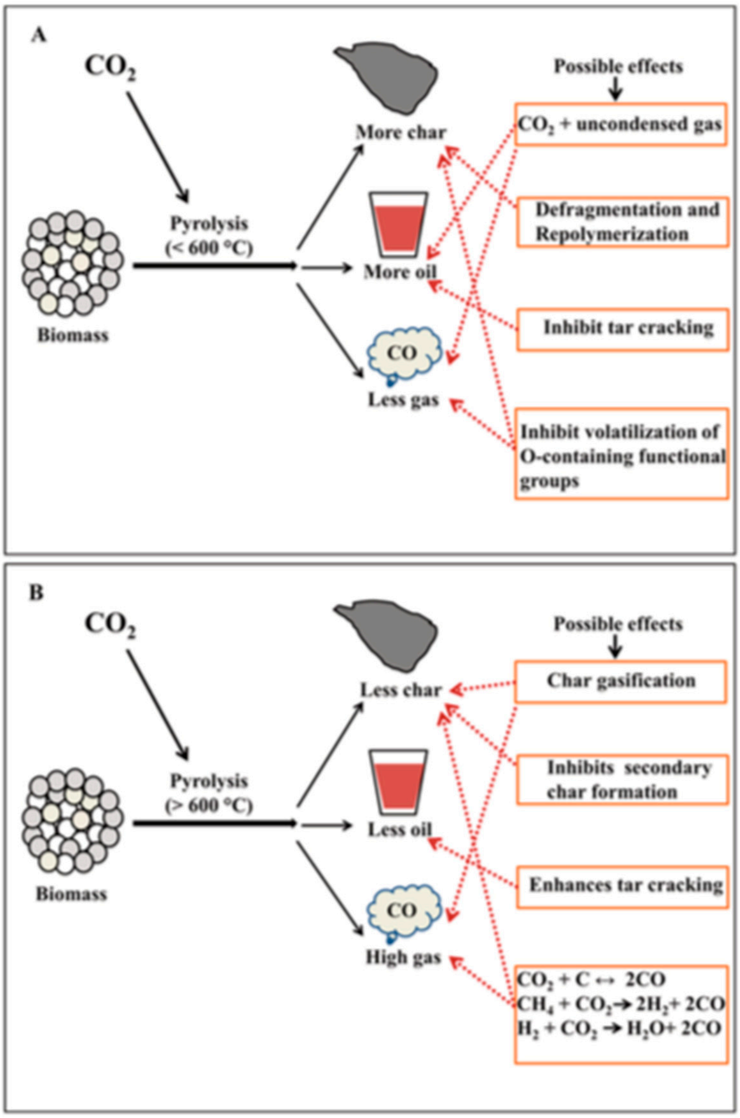

Figure 13. Possible effects of CO_2 on slow pyrolysis at (**A**) lower temperature range (300–600 °C) and (**B**) higher temperature range (600–800 °C). Adapted from reference [17].

6. Future Perspectives

The next step for GCM/GCN is industrial valorization. Indeed, the sustainable perspective concept of biorefineries has long been foreseen [62]. However, improving the economics of conversion technologies is a key step towards the sustainability of the valorization steps that are being proposed [63]. One of the applications that has undergone significant technological development in the last few years is the green chemistry around biomass conversion into liquid fuels and bio-asphalt through bio-oil production [64–66]. This example should be generalized for the valorization of GCM/GCN. Moreover, the future of sustainable technological applications of green carbon materials requires the large-scale, low-cost, scalable, and environmentally friendly production of the nanostructuring and functionalization precursors of carbon materials [67]. Green synthesis methods for carbon nanomaterials, such as wool-based precursors, are being explored [68].

Nanocarbon materials, including fullerene, graphene, and carbon nanotubes, are crucial in developing sustainable energy technologies like the next generation of solar devices and energy storage solutions, resource recovery in electronics, and environmental remediation [69–71]. Pribat (2011) emphasizes the combination of graphene and carbon nanotubes and discusses their use in molecular electronics [72]. Yusof (2019) explores their potential in sensor technology and a range of electronic and optoelectronic devices [73].

These materials possess unique properties, such as excellent electrical, thermal, and optical characteristics, making them suitable for drug delivery, bioimaging, biosensing, and tissue engineering [74]. The surface functionalization of these materials can enhance their properties, such as their drug loading/release capacity and biocompatibility [75]. Graphene-based nanomaterials have also shown promise in disease detection, diagnosis, and treatment [76].

The potential of advanced technologies utilizing carbon-based nanomaterials can be used to offer solutions to contemporary environmental challenges like air, soil, and water degradation. Electrically conductive membrane processes, incorporating separation with a functional surface, are emphasized, focusing on laser-induced graphene and carbon nanotubes as electrically conductive carbon nanomaterials. This material can be used in various environmental applications, including the development of fouling-resistant systems for desalination, water treatment, improved separation methods, and innovative pollutant sensing and electrocatalytic platforms [77].

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