Review

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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 wastes, ought to be used to make processes sustainable and carbon neutral. Carbon nanomaterials, like, for example, carbon dots and nanobichar families, and carbon materials, like activated carbon and biochar substances, are sustainable materials with great potential to be used in different technology 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; wastes; biochar; nanobiochar; sustainability

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 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 some specific functionality needs improved performance, by mixing with specific reagents (Figure 1). For example, carbon nanomaterials obtained directly from biomass usually have low quantum yield (QY). However, mixing with citric acid and a nitrogen source increased the QY to 61%, which is more suitable for chemical/biochemical sensor research [19].

GCM are produced as a by-product of the GCN synthesis or using carbonization or pyrolysis technologies. For example, biomass as raw material for GCN production originated 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 carbonaceous material produced from renewable biomass or wastes that 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].

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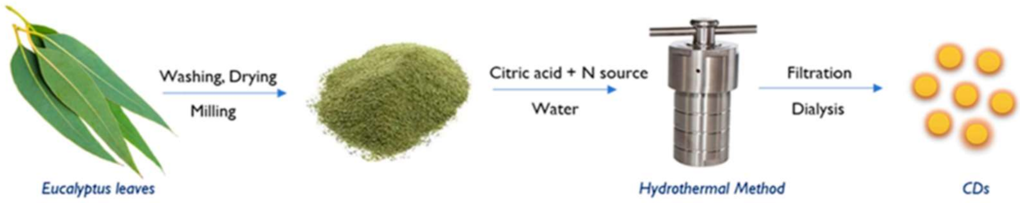

Figure 1. Typical scheme of carbon-based nanomaterial preparation from eucalyptus leaves. Adapted from reference [19].

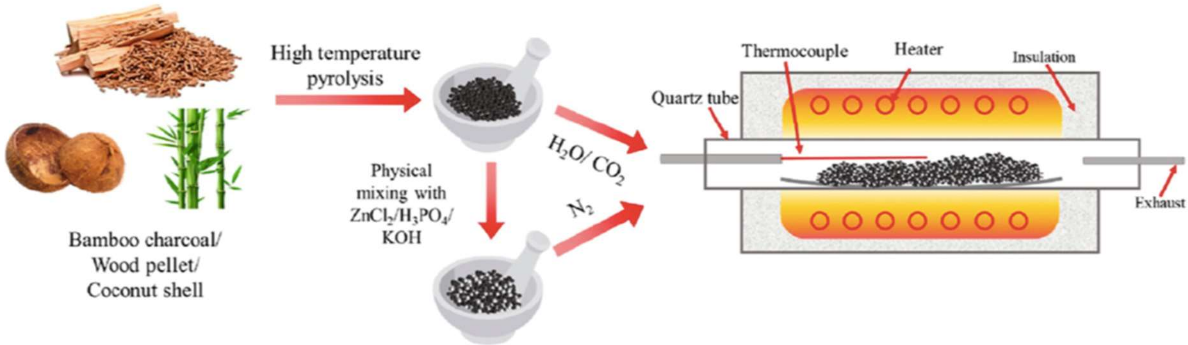

Figure 2. Schematic representation of biomass pyrolysis and biochar activation processes [15]. Copyright {2023} from the American Chemical Society.

To promote technological nano/bulk materials sustainability, raw materials must be obtained from renewable sources or from the recycling of wastes. Regarding carbon-based nanomaterials/materials, straightforward sources of raw materials are renewable biomass and anthropogenic/technological wastes. Using 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 increasing yield production, usually based on unsustainable agricultural practices;

(ii) technological strategies to treat water, either fresh or wastewater, that 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 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 uses carbon nanomaterials synthesized from renewable carbon residuals in the last two years (since 2022), assuring its intrinsic sustainability in those processes.

2. Agriculture applications

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2.1. Carbon bssed nanomaterials

Traditional agricultural NPK inorganic fertilization markedly contributes to the carbon footprint of products, contributing negatively to the sustainability of agricultural farms. Carbon nanomaterials (CNM) are being proposed as potentially more sustainable agents to be used in agricultural practices [20,21]. Although there is no common effect on all plants of the CNM, 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 [20,21], which are not synthesized from renewable biomass and sustainability is compromised.

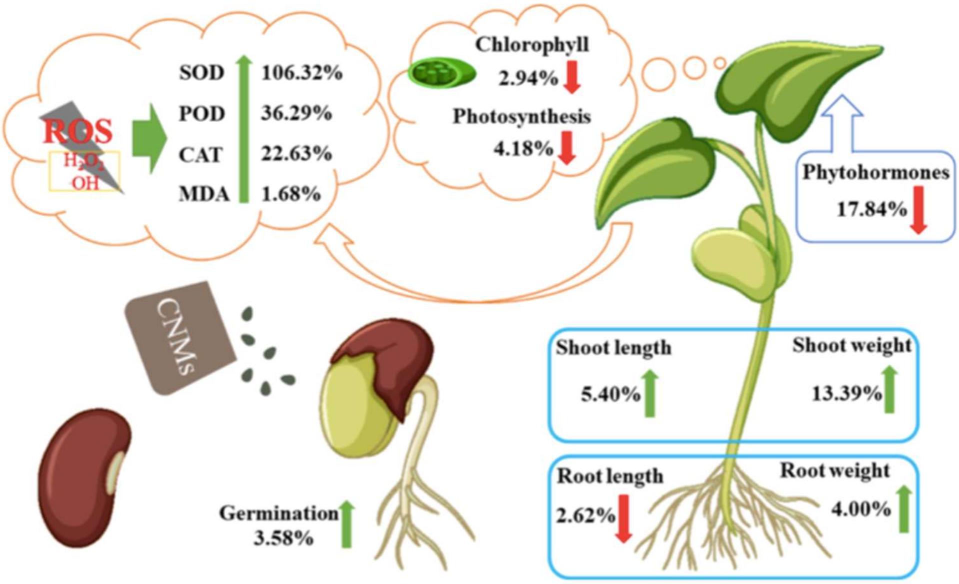

Figure 3. The effect of carbon-based nanomaterials (CNMs) on plants [20]. Copyright {2023} from the American Chemical Society.

Nitrogen doped carbon dots (N-CD) were synthesized from fresh betle leaves (Piper betle) [22]. Namely, 5 g of betle leaves finely cut into pieces were mixed with 60 mL of water and kept at 180 ºC for 10 hours, and N-CD solution was obtained after 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 strawberries irrigated with water and regular nutrients. The N-CD have a marked positive impact on strawberry production compared to the two control experiments (Figure 4). The nanoparticles' water solubility and nanometer size allow their assimilation by the strawberries' roots and increase chlorophyll, phenol and carbohydrate contents [22].

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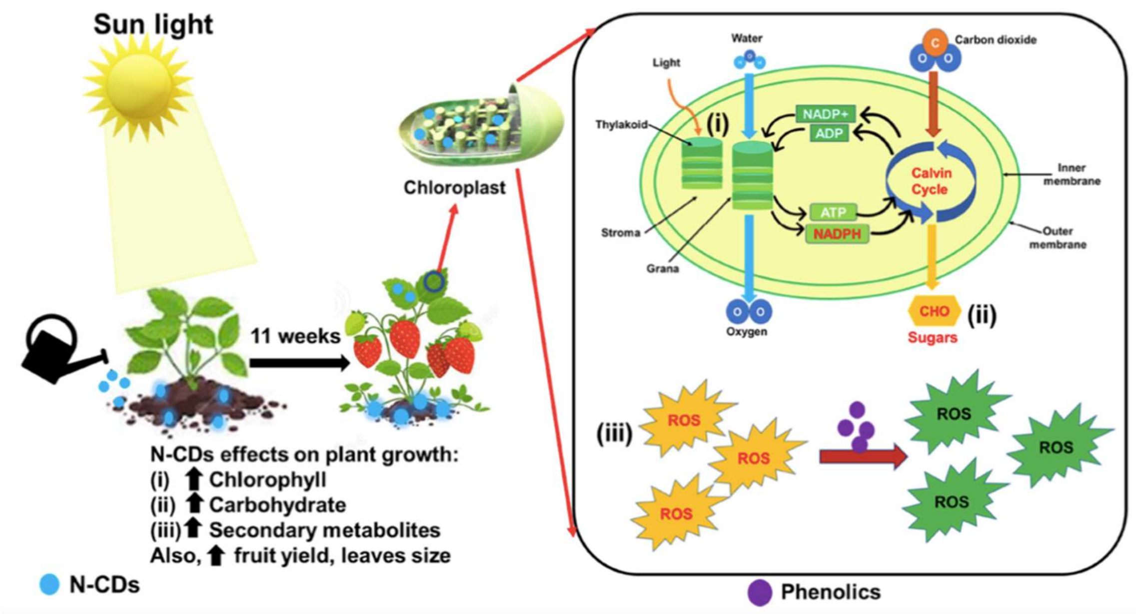

Figure 4. Proposed mechanism of CDs effects on strawberries [22]. Copyright {2023} from the American Chemical Society.

Carbon dots produced from sugar beet molasses (a by-product of sugar factories) (MCD) were assayed for the alleviation of the effect of drought and salt stress on tobacco plant growth [23]. MCD were obtained directly from the supernatant of the centrifugation of the mixture of 5 g of molasses and 10 mL of water [23]. The effect of the increasing MCD concentration solutions on the tobacco plant was observed by replacing irrigation water by the MCD solution. When the carbon nanomaterials were present, the tobacco plant was more resilient under salt and drought stresses [23].

Carbon-based nanomaterials can also be applied to the materials used in greenhouse coverings. Carbon Quantum Dots (CQD) from agave fibers bagasse (obtained from a tequila distillery), were synthesized by burning them in the open-air powder (sieved with a 200 mesh) at 500 ºC between 0.5 to 2 h [24]. CQD were obtained by 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 quantum yield (QY) of the CQD varies from 9.17 to 15.74 depending on the combustion time – the higher the combustion time the higher the QY. The average size of the carbon nanoparticles in the 0.5h combustion time sample was 5.6 nm ± 1.2 nm [24]. 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 is expected to be contaminated with molecular substances resulting from the combustion process. This CQD were applied on acrylic sheets, resulting in a coating that was used in a greenhouse experiment [24]. The CQD coating filters the sunlight with a two-fold benefit on plants: (i) they absorb harmful solar photons; and, (ii) they convert higher energy photons into lower energy blue radiation that matches the absorption of chlorophyll a. The plants (ipomea) under this CQD coating had faster germination rates and better plant growth rates [24].

Due the nanometric size of Carbon dots (CDs) they enter plants by root and leave absorption and may interfere in the plant physiology (Figure 5) [25]. CDs will increase crop yield by enhancing plant photosynthesis, acting as nanofertilizers, promoting good seed germination by facilitating water absorption, improving plant resistance to abiotic stress and inactivating toxic pollutants [25].

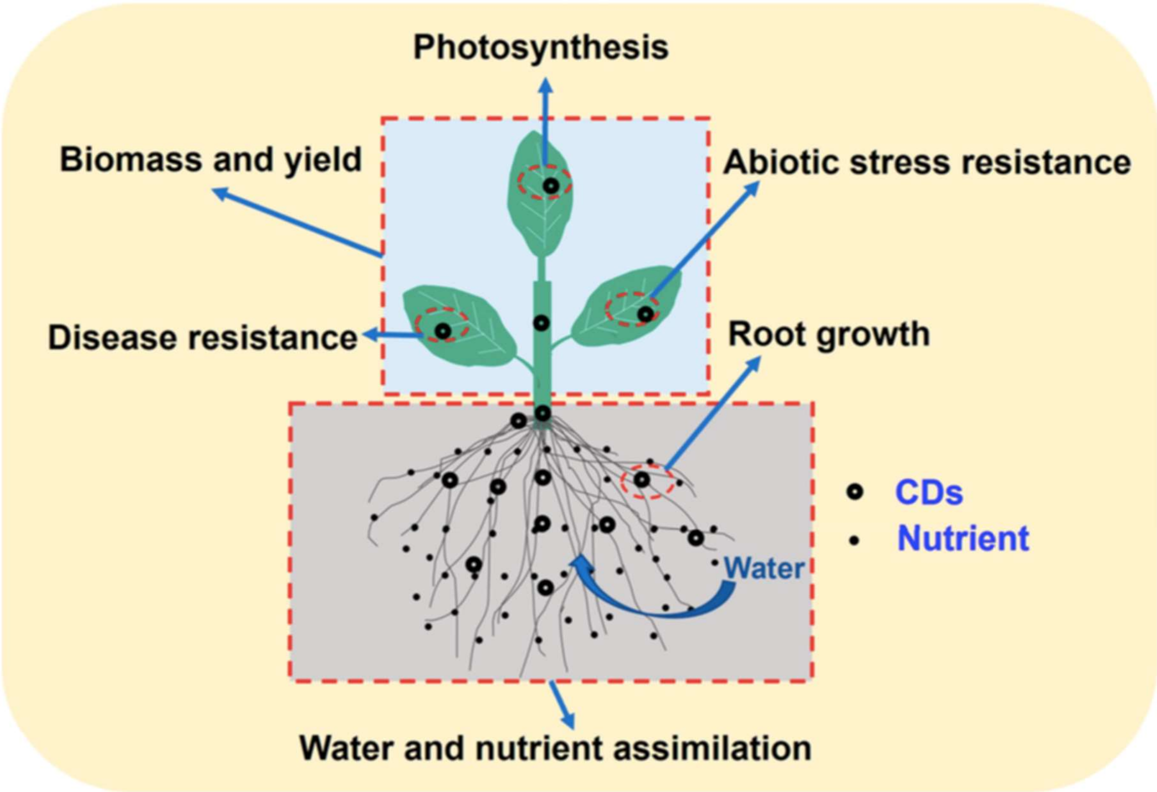

Figure 5. Physiological functions of CDs on plants. Adapted from reference [25].

CNM have another important role in agricultural practices, namely nanocarriers for pesticides and fertilizers, allowing the controlled release of active molecules [20]. Nevertheless, CNM must have intrinsic sustainability, *i.e.* being synthesized from renewable raw materials, and, in the agriculture business, incorporating agricultural residuals in the productive cycle is highly encouraged according to the ongoing transition into the circular economy.

2.2. Carbon based materials – biochar

One of the biomass-based carbon materials that currently has been highly investigated is biochar. Biochar is a product of the valorization of feedstocks, like municipal organic wastes and agri-industrial residues, through slow pyrolysis [26-35]. 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) [26-29]. These features can be tuned using different raw materials and pyrolysis technical characteristics. Biochar is added to soil to modify its physical and chemical composition, microbial activity, soil fertility, and pollution load [26-35].

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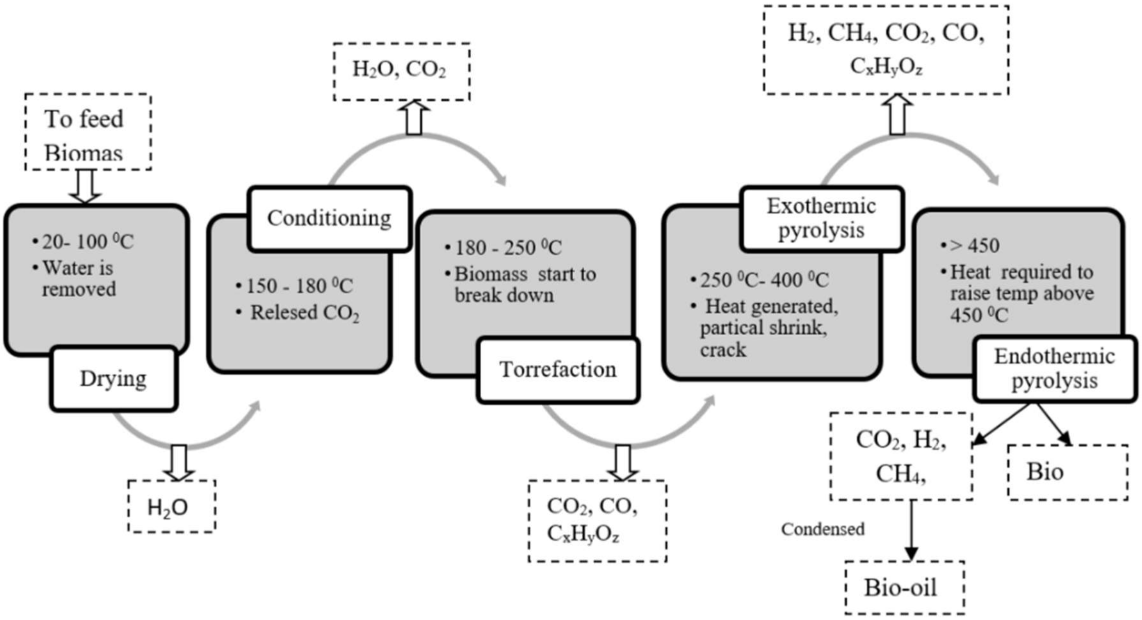

Figure 6. Biochar production process. Adapted from reference [29].

Biochar contains inorganic elements that are macronutrients, particularly N, P and K, and micronutrients to plants and, when added to soils, will improve its fertility, resulting in high crop yields [26,27]. 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, for example, bulk density, porosity, water retention and hydraulic conductivity, that result in an increase in the plant nutrient use efficiency [26,27]. Improved soil organic matter (SOM) and the corresponding soil structure (macro and micro aggregates) are observed upon biochar soil incorporation [29]. Biochar can also stimulate soil microbial population and activity, in particularly mycorrhizal fungi [26,27]. Another essential property of biochar is its specific surface area (SSA) and adsorption of organic compounds and metal ions, which can improve the soil quality by immobilizing toxic pollutants [26]. Also, biochar can be used to correct the pH in acidic soils and/or improve its cation exchange capacity (CEC) [26,27]. Figure 7 resumes the effect of adding biochar to the soil physic-chemical properties [27].

However, biochar is not a well-defined chemical substance with constant properties. Indeed, the biochar's characteristics and its functional properties depends on the raw materials and on the technical features of the pyrolysis [27]. Some examples demonstrate this variability and potential to tune accordingly the desirable application [27]:

(i) The pyrolysis of hardwood biomass results in a biochar with higher organic carbon. If biochar is made from animal manure it results in a higher NPK nutrient load and a higher CEC [26]. Different raw materials induce a nutrient-enriched biochar [30]: seaweed, potassium; manure, phosphorous; rice straw, silicon; bone, calcium; keratin, nitrogen.

(ii) Higher pyrolysis temperature produces a biochar that raises nutrient concentration, soil porosity, SSA and carbon content and increases pH [27]. Biochar produced at lower temperatures improves soil CEC [26].

(iii) High-temperature biochar produced from lignin-rich feedstocks may decrease methane and nitrous oxide emission in acid soils and contribute to carbon sequestration [28]. Low-temperature biochar from manure is reached on nutrients and improved crop yield in low fertility soils [28].

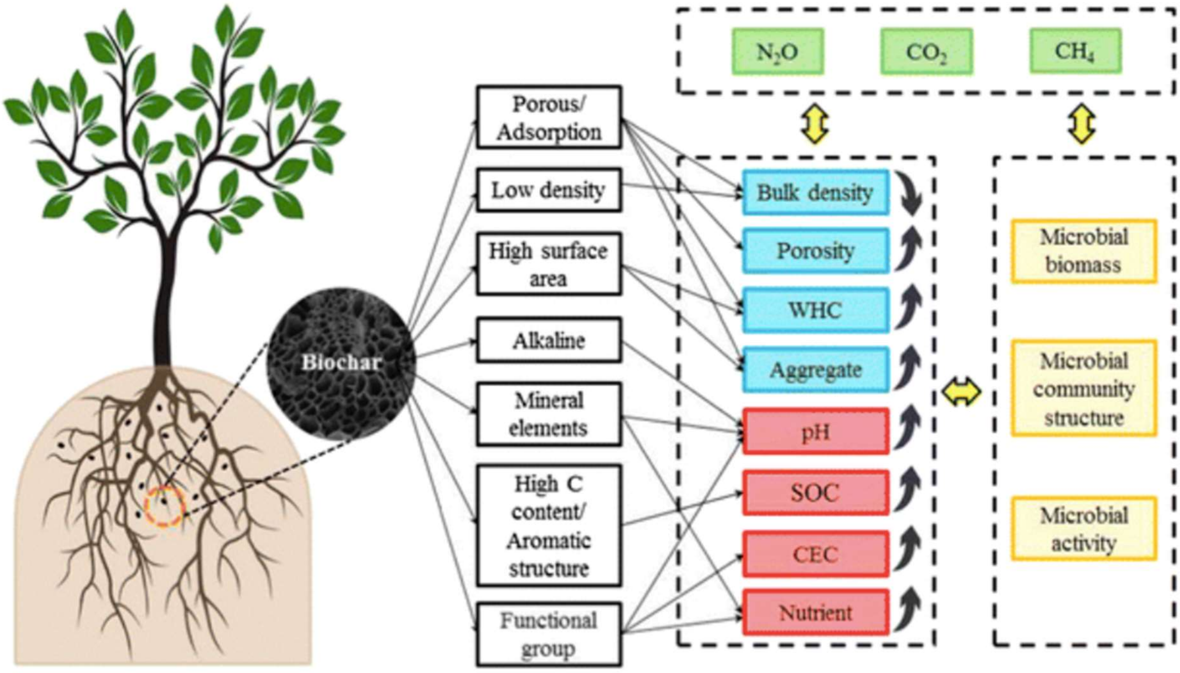

Figure 7. Effect of adding biochar to soil physic-chemical properties. Adapted from reference [26].

Biochar has been used as a growing medium in hydroponic cultures [29]. Also, biochar has been used to amend composting processes to reduce greenhouse gas emissions and nitrogen loss [29].

Slow-release fertilizers (SRFs) are a solution to the nutrients loss from the soil through leaching, volatilization, denitrification and surface runoff, and biochar SRFs (BSRFs), derived from agricultural wastes, are being proposed as a more sustainable alternative [30-32]. BSRFs are obtained by copyrolysis of biomass with a chemical substance that contains the nutrient, for example, phosphate rock or urea [30].

In the last years, nanobiochar has been proposed as a way to combine the positive properties of the material with those of the nanomaterial [36,36]. A study on the foliar spray of nanobiochar in cauliflower production showed beneficial effects on crop yield and quality of the cauliflower [36]. In a study about corn nutrient uptake from farmyard manure, low concentrations of nanobiochar significantly improved microbial biomass and increased macronutrient uptake, indicating a positive impact on the soil microorganisms and their activity [37]. However, when higher concentrations of nanobiochar were used, toxicity was observed [37].

3. Water treatments

Due to the ubiquitous environmental contamination and the increase in public and regulatory environmental agencies' awareness about water quality, water treatment is becoming more challenging. Carbon nanomaterials are being proposed to incorporate advanced water treatment technologies [38-40]. 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 the GNN and GCM have the potential to be used in environmental remediation technologies.

Carbon dots (CDs) synthesized by an eco-friendly hydrothermal approach from brewing waste, spent grains and spent yeasts were used as photocatalysts for wastewater treatment [41]. Nitrogen doping CDs, with an average size of about 100 nm, were produced by hydrothermal carbonization (24h at 200ºC) of the brewing wastes mixed with water or residual beer and purified by dialysis after centrifugation and isolated as a solid after freeze-dried. In this work, the carbon nanomaterials presented in the solution were isolated, and the insoluble material was discarded. CDs 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 [41].

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CDs synthesized from fresh guava leaves (*Psidium guajava*) were used to cleanup oil spills [42]. CDs, 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 70ºC for 2 hours; after filtration, the solution was carbonized using a 600 W microwave for 5 minutes; the obtained solid sample was washed with water and dried at 60ºC for future use. An ethanol suspension of the CDs (1.5 mL of 33.32 mg/mL) was added to a 200 mg cotton piece and left to dry at room temperature. The CDs coated cotton (CDC) was used for the cleanup of oil spills [42] (Figure 9).

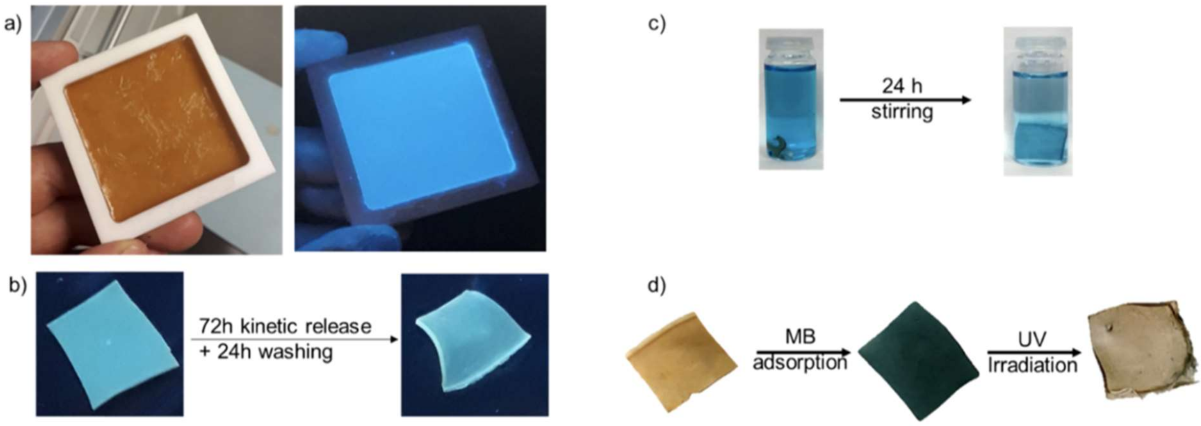

Figure 8. (a) PVA-CD hydrogel under visible light and UV light, (b) PVA-CD hydrogel fluorescence before and after washing treatment, (c) MB absorption test on PVA4 hydrogel, and (d) PVA4 hydrogel before and after MB absorption and after 24 h of UV irradiation [41]. Copyright {2022} from the American Chemical Society.

Green carbon quantum dots (GCQD) were prepared from extracts of fresh guava leaves (*Psidium guajava*) by a hydrothermal process at 200ºC for 5 hours [43]. Purified powdered GCQD were obtained by lyophilization after centrifugation and filtration using a 0.22 mm filter. GCQD had a normal size of 1.27 nm and a quantum yield of 32%. The effect of GCQD 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 minutes [43]. A carbon nanomaterial (with a size in the range of 63 to 137 nm) was synthesized from *Spirulina platensis* aqueous solution (a 100 mg/mL solution was centrifuged and diluted 1:5 with water), by following method:

(i) the solution was processed by microwave-assisted technology (800 W for 60 minutes);

(ii) centrifugation to remove precipitated material, followed by diluting 1:1 with water, followed by second processing with a microwave oven for 30 min at 800 W;

(iii) centrifugation 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. A dye degradation of 95,5% was achieved after 6 hours following first-order kinetics. The degradation of the dye to smaller, easily degraded molecules was confirmed by GC-MS [44]. In another study with this carbon nanomaterial produced from *Spirulina platensis*, 90-97% of textile effluents were successfully photo-degraded using 1 mg/mL concentration [45].

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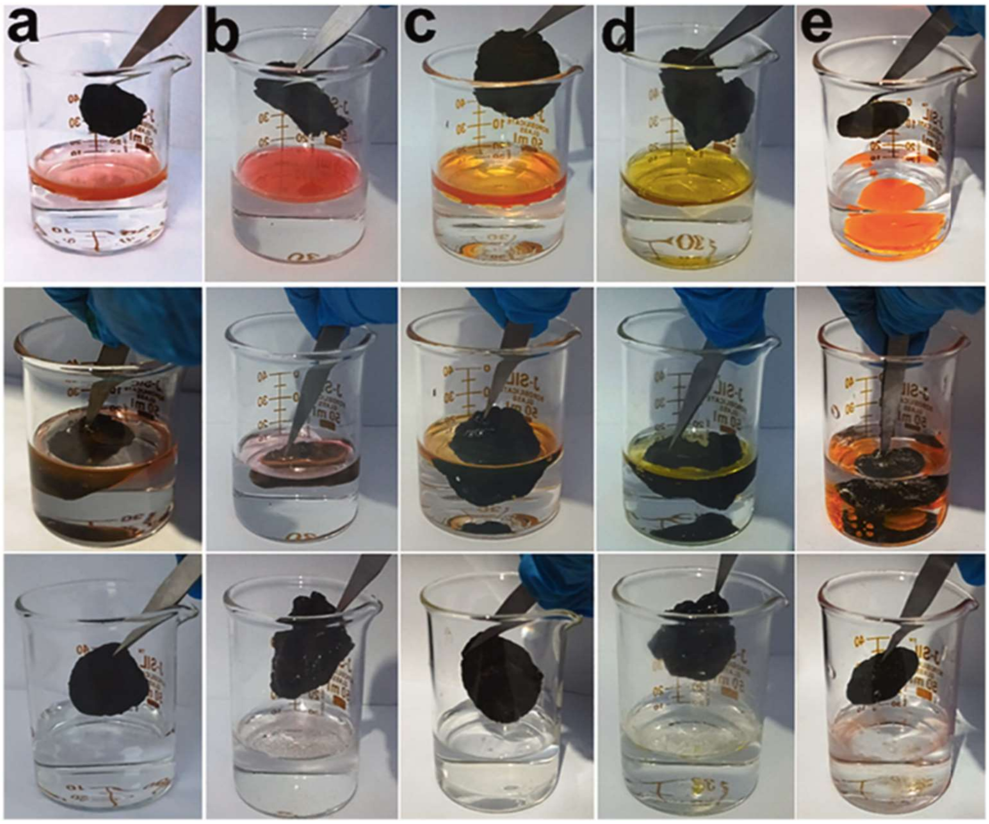

Figure 9. Cleanup of light and heavy oils [a) silicon oil, b) refined oil, c) motor oil, d) mustard oil, and e) carbon tetrachloride] from the oil-water mixture by CDC at room temperature. For better visualization, Nile red dye was added with silicon oil, refined oil, and carbon tetrachloride [42]. Copyright {2022} Elsevier Ltd..

A standard, well-known material that is commonly used in water/wastewater treatment stations is activated carbon (AC), which can be produced from biomass (Figure 10) [46]. AC are 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 [46].

Another emerging area of research is the use of renewable biomass for the production of GCN to be used in water disinfection as an alternative to chlorine and to minimize the disinfection by-product generation. Carbon dots were prepared from coconut wastes by hydrothermal carbonization and pyrolysis followed by sonication and doped with urea, polyethyleneimine (PEI) and hexamethylenetetramine (HMTA), which had enhanced antibacterial properties [47]. 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 [47].

GCN synthesized by microwaves are being proposed in water treatment applications [48]. The use of microwave reactors adds more sustainability to the carbon-based materials because fast reactions, and consequently less 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 do not emit carbon dioxide or methane, as observed when simple synthetic chemical substances are used as raw materials [48]. The synthesized GCN are mainly used in environmental treatment as adsorbents of chemical pollutants [48].

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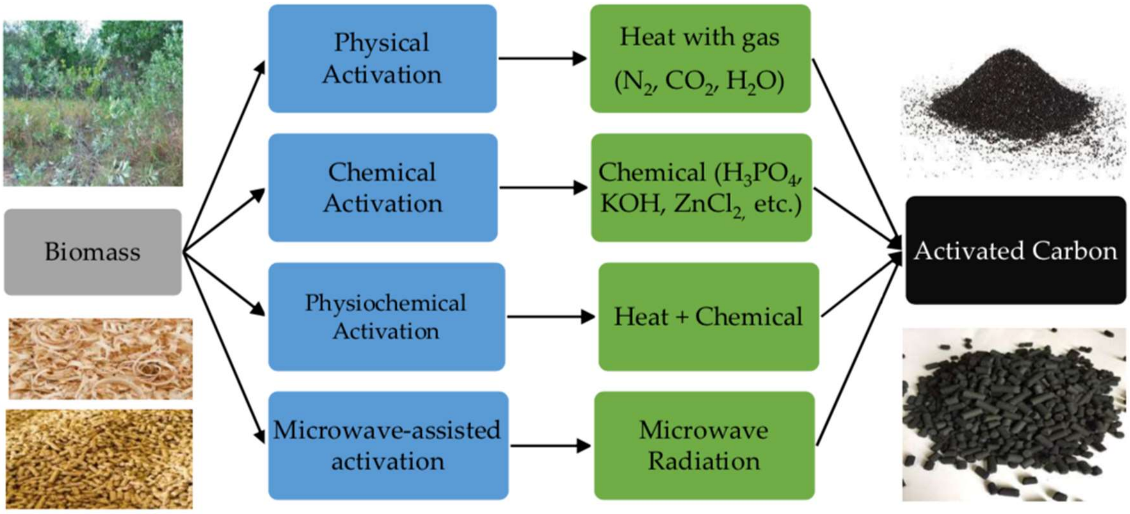

Figure 10. Technologies for activated carbon preparation from biomass. Adapted from reference [46].

Biochar type materials were prepared from the pyrolysis (700 ºC, retention time of 2.5 hours, and heating rate of 5 ºC/min under nitrogen) of corn stover [49]. This carbon-based material was used to remove cadmium (II) ions from water with a maximum adsorption capacity of 13.4 mg/g [49]. Biochar has been used to remove heavy metals from aqueous solution due to its large SSA and precipitation of the metal hydroxides due to the high pH and surface O/C ratio and polarity [50].

Although biochar research in agriculture is a well-established area, its nanosized fraction, nanobiochars, are in the first steps of scientific research. Nanobiochars are being proposed for environmental remediation, although its mechanism of action is poorly known [51-54]. Nanobiochar has superior physicochemical properties than biochar, such as high catalytic activity, large SSA and high environmental mobility [51]. The main applications of nanobiochar in environmental treatment technologies are in pollutant removal like heavy metals, toxic organic substances and emerging pollutants by adsorption mechanisms like ion exchange, complexation, precipitation, electrostatic interaction and physical adsorption [51-53]. As discussed above, 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 [52,53]. The temperature is a critical factor for the nanobiochar functionality, for example, the SSA, ash content and carbon content increase with the pyrolysis temperature, although this effect is raw material dependent [54]. Lower pyrolysis temperature nanobiochar resulted in abundant surface functional groups, high absolute zeta potential and strong suspension stability [54]. Nevertheless, the properties of nanobiochar, like those of biochar, are raw material dependent, and each product must be assayed and its properties tuned for the type of specific application desired.

Nanobiochar enhanced with magnetic properties have been proposed for technological applications [52]. They are prepared from ball milling of biochar produced from biomass mixed with an inorganic magnetic precursor. In water treatment, they are being assessed for the adsorption of toxic heavy metals and pharmaceutical water pollutants [52].

4. Energy management

In the context of the present energy transition into 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. [46]. 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 [46].

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Corn leaf waste was carbonized in the temperature range between 400 and 600 ºC (heating period of 5 ºC/min with a dwell period of 2 hours) to obtain a biocarbon [55] (Figure 11). The 600 ºC biocarbon was ball-milled for 2 hours at 250 rpm, followed by treatment with hydrochloric acid for 30 minutes at 50 ºC (sample C600B). The ball-milling and washed treatments generated particles with a size less than 20 µm and with lower impurities. This biocarbon sample was used to assemble electrodes as anode material for Na-ion batteries using carboxymethyl cellulose as a binder [55]. The electrochemical performance of the C600B sample is: a capacity of 171 mAh g^{-1} after 10 cycles at 100 mA g^{-1}; the Na-ion storage capacity of 134 mAh g^{-1} after 100 cycles; and charge-transfer resistance and Na-ion diffusion coefficient was, respectively, 49 Ω and 4.8×10^{-19} cm^2 s^{-1} [55].

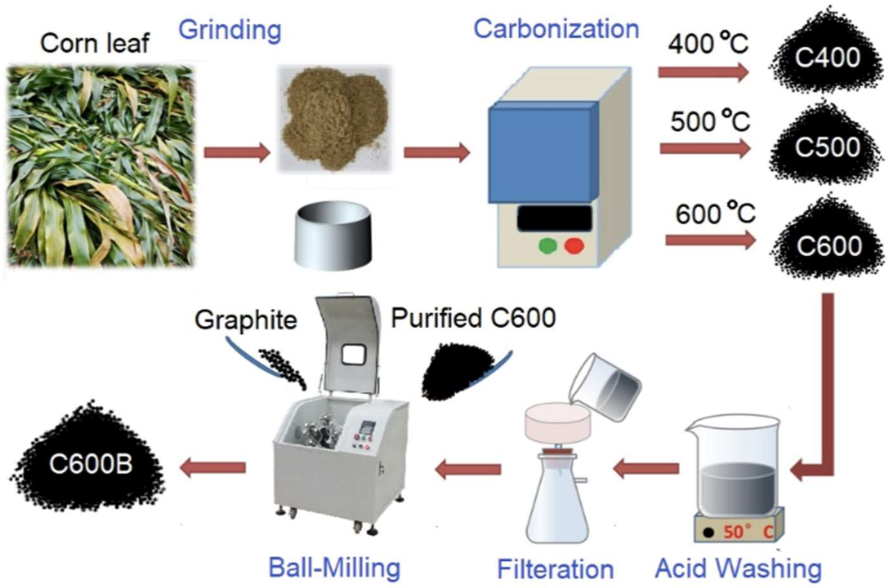

Figure 11. Scheme of the carbon material preparation from corn leaf. Adapted from reference [18].

Research in carbon nanoparticles to be used in high-performance rechargeable batteries is increasing due to their supreme conductivity values and excellent mechanical stability [56]. Indeed, increasing their storage capacity, particularly gravimetric capacitance, cyclic stability, and densities (energy and power), is necessary for the next generation of sustainable supercapacitors [56].

5. CO_2 reduction and sequestration

The ongoing climate change due to the increased atmospheric concentration of greenhouse gases (GHG) has justified the current carbon neutrality objectives defined by the COP's regular meetings and by regional or country-specific regulations. By the middle of the current century, emissions of carbon dioxide equivalent 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 will have to increase 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 to 200 °C for 18 hours [57]. 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. This CQD catalyzed the reduction of CO_2 into CH_4 in water with an evolution rate of 99.8 nmol/g at 436 nm [57].

One of the technologies for CO_2 capture is its sequestration in a solvent, and the most known is monoethanolamine (MEA). Activated carbon (AC) has shown a sustainable potential to replace MEA as an adsorbent for CO_2 [46]. AC from Paulownia sawdust, using a production temperature of 1073 ºC and KOH as the activation agent, has a CO_2 adsorption capacity of 7.14 mmol/g at 273 K [46]. The

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production of AC with surface amino functional groups and large surface area improves the CO_2 sequestration potential [46].

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 [13-18,57-59]. Indeed, a net emission reduction in the range of 0.4-1.2 Mg CO_2 equivalent 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 potential for carbon sequestration (Figure 12) [13].

Biochar, like AC, discussed previously, can also be directly involved in technological CO_2 capture processes [14-16]. However, the intrinsic CO_2 sequestration potential of biochar is low, and, like AC, it needs to be activated in order to become an alternative to current capture technologies. The 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 done by mixing the reacting biomass with CO_2 and/or H_2O during the biochar production, and chemical activation is achieved by reaction with strong bases, acids and molten salts [14-16]. Also, considering the acid properties of CO_2, surface functionalization with alkaline amine groups would optimize the CO_2 capture potential [15].

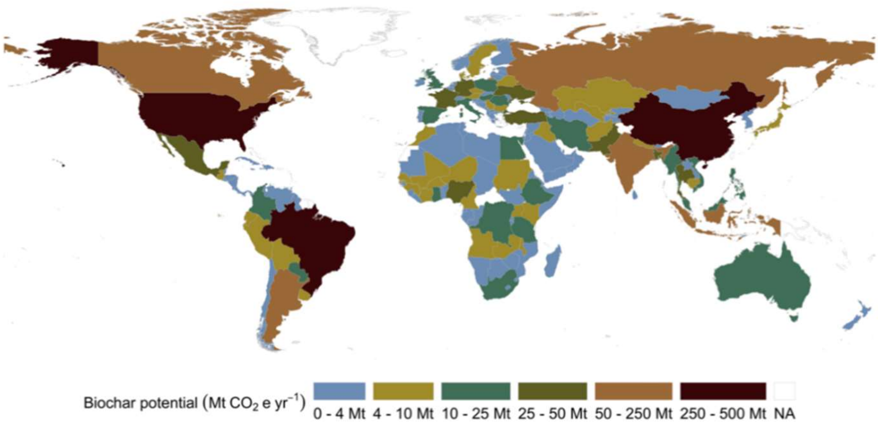

Figure 12. Global biochar carbon dioxide removal potential map (Mt CO_2e year^{-1}). Adapted from reference [13].

The concept of climate-smart agriculture originated from the carbon neutrality objectives to be accomplished in the middle of the current century [27]. The impact of biochar on the percentage of soil organic carbon (SOC), methane and nitrous oxide emissions, and crop yield is being assessed as an agricultural practices [27,58,59]. For example, the application of biochar in farmlands in China increases SOC by 1.9 Pg C and reduces CH_4 and N_2O emissions by 25 and 20 Mt CO_2 eq./year, respectively [27].

Biochar is produced under an inert atmosphere to inhibit oxygen oxidation of the organic matter, for example, nitrogen, by thermal treatment at high temperatures. However, if carbon dioxide is used instead of inert gas and 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 becomes an improved carbon footprint, contributing to mitigating global warming. Also, the properties of this biochar become different from those produced under an inert atmosphere, and the differences depend on the temperature used in the synthesis process, as is resumed 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].

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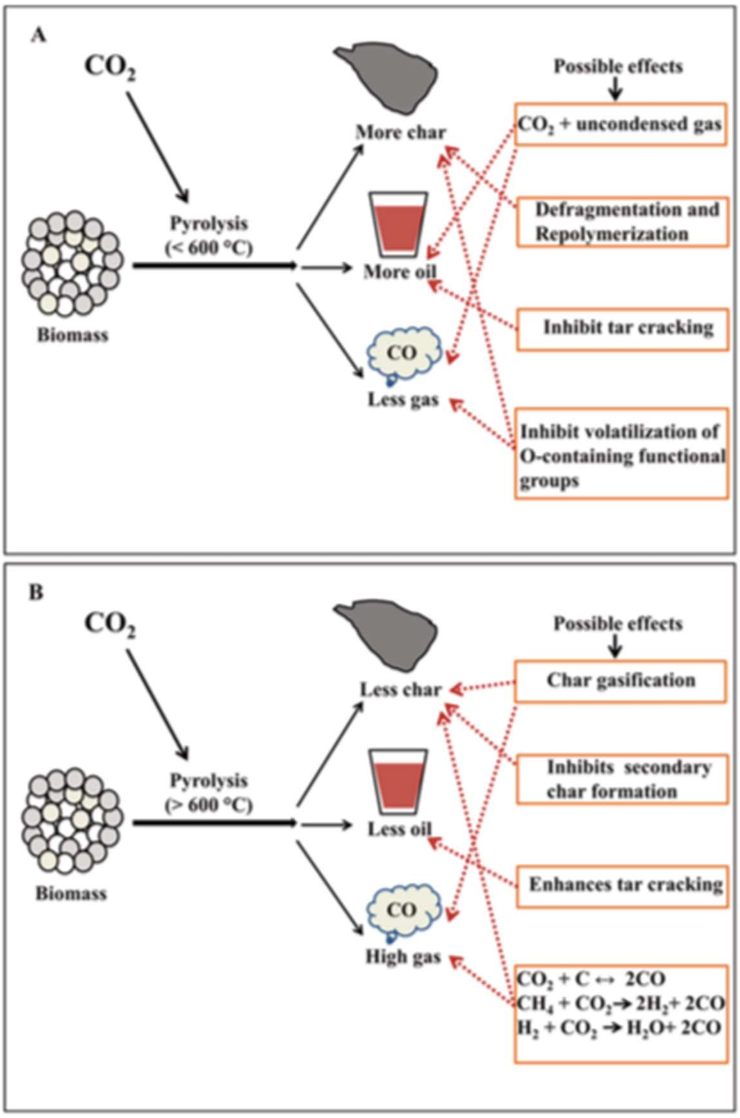

Figure 13. Possible effects of CO_2 on slow pyrolysis at (A) lower temperature range (300–600 ºC) and (B) higher temperature range (600–800 ºC). Adapted from reference [17].

6. Future perspectives

The future of sustainable technological applications of green carbon materials undergoes large-scale, low-cost, scalable, and environmentally friendly production of the nanostructuring and functionalization precursors of carbon materials [60]. Green synthesis methods for carbon nanomaterials, such as wool-based precursors, are being explored [61].

Nanocarbon materials, including fullerene, graphene, and carbon nanotubes, are crucial for developing sustainable energy technologies like the next generation of solar devices and energy storage solutions, resource recovery in electronics, and environmental remediation [62-64]. Pribat (2011) emphasizes the entanglement of graphene and carbon nanotubes and discusses their use in molecular electronics [65]. Yusof (2019) explore their potential in sensor technology and a range of electronic and optoelectronic devices [66].

These materials possess unique properties, such as excellent electrical, thermal, and optical characteristics, making them suitable for drug delivery, bioimaging, biosensing, and tissue engineering [67]. Surface functionalization of these materials can enhance their properties, such as drug loading/release capacity and biocompatibility [68]. Graphene-based nanomaterials have also shown promise in disease detection, diagnosis, and treatment [69].

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The potential of advanced technologies utilizing carbon-based nanomaterials can be used to offer solutions for 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 developing fouling-resistant systems for desalination, water treatment, improved separation methods, and innovative pollutant sensing and electrocatalytic platforms [70].

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