IUPAC Technical Report

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Glossary of terms used in biochar research (IUPAC Technical Report)

https://doi.org/10.1515/pac-2021-0106 Received January 4, 2022; accepted May 22, 2024

Abstract: Biochar is the solid carbonaceous product of biomass pyrolysis. The properties of biochar depend on the biomass feedstock as well as the pyrolysis temperature and time. Therefore, biochars with different properties and functionalities can be produced. Biochar research has been intensive in the past 15 years, focusing mainly on soil applications, wastewater treatment, and contaminant remediation. However, a formal definition of biochar and related terms is missing, which hinders the standardization of scientific results worldwide and the scaling-up of research at the industrial level. Furthermore, an official terminology may promote the development of a harmonized legal framework for biochar production and applications, both at regional and national levels. This glossary of terms consists of 178 scientifically sound definitions of the most commonly used terms in biochar research. The definitions of this glossary are interconnected, allowing the reader to further explore the synergies between terms. The distribution of terms reflects the multidisciplinarity of biochar research: chemistry, material science and engineering, and soil science are the main disciplines represented here. The list of terms is by no means exhaustive and the strategic objective of this effort is to develop a dynamic document in which more terms will be added in the future, and the existing ones will be refined, as biochar research evolves.

Keywords: biochar; biomass; carbon; circular bio-economy; sustainable development.

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Article note: Sponsoring body: IUPAC Chemistry and the Environment Division: see more details on p. 1568. This manuscript was prepared in the framework of IUPAC project 2015-056-3-600.

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1 Introduction

Biochar is a carbon rich, solid material resulting from the pyrolysis of biomass under dioxygen-free or dioxygenlimited conditions at temperatures between 300 and 800 °C. During pyrolysis, the lignocellulosic components of biomass, cellulose, hemicellulose, and lignin undergo depolymerization, fragmentation, and cross-linking at specific temperatures resulting in solid (biochar), liquid, and gaseous products [1, 2]. The liquid products consist of bio-oil, whereas the gaseous products are carbon dioxide, carbon monoxide, hydrogen, and lower molecular weight hydrocarbons.

The type of biomass, pyrolysis temperature, and heating rates are the main factors that determine biochar properties such as fixed carbon, mineral phases, surface area, porosity and pore size distribution, alkalinity, electrical conductivity, and cation-exchange capacity. The carbon mass in biochars may vary between 50 and 90 %, followed by lower contents of oxygen and hydrogen. Due to its highly variable and customizable surface chemistry, biochar offers great potential in a variety of engineering applications, some of which have yet to be discovered. Although most research is directed toward the application of biochar to soils, there are several other biochar properties that render it a suitable candidate for non-agricultural applications.

Efficient management of bio-degradable waste fractions, such as animal manure and agricultural waste, has been a major problem throughout the world [2]. Especially in developing countries, lack of modernization in farming and processing of agricultural products leads to the disposal of large quantities of waste. Technical, financial, and social constraints further increase the quantities that remain unexploited. Production of biochar through pyrolysis offers a sustainable solution for such waste, with respect to volume reduction, bioenergy exploitation, and added-value materials [2].

Biochar research is highly interdisciplinary – from the use of analytical techniques for its characterization to the development and evaluation of its multiple applications. Two of the main challenges toward a wider and large-scale use of biochar are standardization and regulation. Each biochar batch can be different from the other; even two made one after the other may vary if the process conditions and/or feedstock properties differ slightly. Developing regulations (national or international) for the production, characterization, and applications of biochar is hindered by the lack of standardization both in terms of procedures as well as terminology.

Over the past 20 years, the published literature on biochar has been steadily increasing and expanding in nature. Between 2000 and 2006, there were 12 publications on biochar, investigating the use of the material as a precursor for activated carbon and as a soil amendment. In 2023 alone, there were 5682 published works, dealing with over 20 distinctly different biochar applications (Scopus search, keyword: biochar).

The objective of this study was to provide clear, precise, and comprehensive definitions for terms related to the rapidly developing area of biochar research and application. Due to the interdisciplinary nature of research, the glossary will act as a reference document for the intended stakeholders from different back-grounds and as an introduction to biochar for a wider audience. It will also enhance the efforts for stan-dardization of biochar production, characterization, and applications. This glossary outlines the definition of terms most frequently encountered in the field of biochar research. A Scopus literature search was performed (years 2010–2023) based on the two major aspects of biochar research: production and applications. The following keywords were used, alone or combined: biochar, biomass, pyrolysis, circular bio-economy, carbonization, carbon, soil amendment, carbon storage, greenhouse gases emissions, climate change mitigation, adsorption, soil remediation, wastewater treatment. From the results obtained, the highly cited research articles and review papers were studied and assessed. Then, a list of potential terms was compiled and discussed between authors. As soon as the list was finalized, the IUPAC Gold Book was consulted to determine terms already defined [3]. The definitions of some terms were obtained from highly cited publications, whereas others are defined for the first time. The terms are arranged in alphabetical order with italicized entries defined elsewhere in this document.

2 Glossary of terms

1. abiotic stress

The negative impact on plants, trees, and soil microbiome not associated with living organisms [4]. Abiotic stress originates from naturally occurring, often intangible and inanimate factors such as intense sunlight, temperature, or wind that may cause harm to plants, trees, and soil microbiome. The most common abiotic stress factors include high winds, extreme temperatures, low water and nutrient availability, floods, chemical pollution, and natural disasters such as wildfires [5].

2. absorption

The process of one material (absorbate) being retained by another (absorbent); this may be the physical solution of a gas, liquid, or solid in a liquid, attachment of molecules of a gas, vapor, liquid, or dissolved substance to a solid surface by physical forces [6].

3. acid soil

Soil with a pH value below 7 [7].

See soil pH.

4. active adsorption site

See active site.

5. active site

Phase interface sites that, due to surface forces, have effective increase in the amount concentration of particular *adsorbates* [8, 9].

6. adsorbate

A molecular species of gas, dissolved substance, or liquid which adheres to or is adsorbed in an extremely thin surface layer of a solid substance [10].

See adsorption, adsorbent.

7. adsorbent

A condensed phase at the surface of which adsorption may occur [11].

See adsorption, adsorbate.

8. adsorption

An increase in the concentration of an *adsorbate* at an interface of a condensed phase (*adsorbent*) and a liquid or gaseous layer due to the operation of surface forces [12].

See adsorbent, adsorbate.

9. adsorption capacity

For strongly adsorbed solutes of limited solubility, the value of the mass of adsorbed substance reached in a saturated solution is called the *adsorption capacity* of the *adsorbent* for a specific solute; its value depends also, in general, on the nature and, in the case of more than two components, on the relative composition of the bulk liquid [13].

Note: Commonly determined by fitting isotherm equations to *adsorption isotherm* data and reported as mass mg of *adsorbate* by mass g of *biochar* [14]. It is influenced by properties of the *biochar* such as particle size, surface area, surface *functional group* composition and specifically degree of surface oxidation and hydrophobicity [15], solution pH, dosage of the *adsorbent*, competitive *adsorbates*, electrolyte content of the solution, and temperature [16].

See adsorption, adsorbent, Langmuir isotherm.

10. adsorption kinetics

An experimental process followed by mathematical calculation to determine the true equilibration time and the optimal contact time for *adsorption* processes [17]. It provides insights on how the *adsorbate* uptake rate from either the gas or liquid phase controls the residence time of the *adsorbate* at the solution interface [18].

Note 1: To assess experimentally obtained kinetics data, *adsorption* kinetic models have been developed based on two main classifications, namely, reaction-based or diffusion-based models [18, 19].

Note 2: Reaction-based models describe the rate of *adsorbate-adsorbent* interactions and include commonly known and widely applied *Lagergren pseudo-first* and *pseudo-second order models*. The diffusion-based models however describe the diffusive transport of *adsorbates* from the bulk solution into pore networks and *active sites* of the *biochar* and includes the *Weber and Morris' intraparticle diffusion model* and the *Boyd's model* [19, 20].

See adsorption, adsorbent, adsorption kinetics, Boyd's model, Lagergren pseudo-first order kinetics model, Lagergren pseudo-second order kinetics model.

11. adsorption isotherm

Relationship between the amount, number, or mass of a substance adsorbed and the composition of the bulk phase (or the partial pressure in the gas phase) under equilibrium conditions at constant temperature [21].

See Dubinin–Radushkevich isotherm, Freundlich isotherm, Langmuir isotherm, Redlich–Peterson isotherm, Sips isotherm.

12. adsorption mechanism

The series of steps and/or interactions by which the uptake of *adsorbate* from either a gas or liquid phase onto the surface and/or pores of the *adsorbent* takes place.

Note 1: It usually includes four general steps, namely, (i) bulk diffusion, (ii) *film diffusion transport*/external mass transfer/*boundary layer* diffusion, (iii) *intra-particle/pore diffusion*, and (iv) *adsorption*.

Note 2: The *adsorption* step requires further analysis to elucidate the type or series of interactions responsible for the *sorption*. These may include but are not limited to *micropore* filling, *capillary condensation*, electrostatic attractions or repulsions, cation/anion exchanges, $C-\pi$ cation interactions, $\pi-\pi$ interactions, Yoshida H-bonding, *dipole–dipole H-bonding* and $n-\pi$ interactions, complexation, and/or precipitation [16, 17].

See adsorption, adsorbate, adsorbent.

13. adsorption performance

The amount of *adsorbate* adsorbed on the *adsorbent*'s surface at equilibrium or the proportion of removed *adsorbate* from solution [16].

See adsorption, adsorbate, adsorbent.

14. adsorption selectivity

The relative strength of *adsorption* of different *adsorbate* molecules depending on the relative magnitudes of the polarizability, dipole moment, and quadrupole moment of each [16].

See adsorption, adsorbate, adsorbent.

15. adsorption site

The volume element or location on the surface of biochar where adsorbates can be adsorbed [9].

See adsorption, adsorbate, adsorbent.

16. adsorption thermodynamics

A mathematical description of the effects of temperature/heat changes on the *adsorption* process and subsequent elucidation of the mechanism (*physisorption* or *chemisorption*), spontaneity, and endothermicity or exothermicity of the *adsorption* process. A plot of $\ln K_c$ against the inverse of temperature, *T* (K), using the linear form of the Van't Hoff equation yields a gradient and an intercept for computing the thermodynamic parameters.

$$\ln K_c = \frac{-\Delta_r H^{\ominus}}{R} \left(\frac{1}{T}\right) + \frac{\Delta_r S^{\ominus}}{R}$$

where K_c is the equilibrium constant; $\Delta_r H^{\ominus}$, J mol⁻¹, is the enthalpy change; $\Delta_r S^{\ominus}$, J mol⁻¹ K⁻¹, is the entropy change; R, J mol⁻¹ K⁻¹, is the universal gas constant; and T, K, is the temperature.

Note 1: To assess the spontaneity of *adsorption*, the Gibb's energy change, $\Delta_r G^{\ominus}$ (J mol⁻¹) is calculated from: $\Delta_r G^{\ominus} = -RT \ln K_c$

Note 2: Values of K_c can be obtained from adsorption isotherm constants or the partition coefficient [11].

Note 3: Values of $\Delta_r H^{\ominus}$ for *physisorption* usually are below 80 kJ mol⁻¹, whereas values greater than 80 kJ mol⁻¹ indicate chemisorption [22].

See adsorption, adsorbate, adsorbent.

17. alkaline soil

Soil with a pH value higher than 7 [7].

See soil pH.

18. amazonian Dark Earth

See Terra Preta soil.

19. anion exchange capacity

The sum total of exchangeable anions that a material can adsorb. Expressed as centimoles or millimoles of charge per kilogram of adsorbing material (*e.g.*, soil, clay, or *biochar*).

20. arbuscular mycorrhizal fungi

Soil-born fungi (*Glomeromycota*), obligate symbionts of a very wide range of plant species. The symbioses are biotrophic and normally mutualistic, the long-term compatible interactions being based largely on bidirectional nutrient transfer between the symbionts. The plant provides photosynthetic carbon to the fungus and the fungus supplies nutrients with poor mobility in soil, particularly phosphorus, sulfur and micronutrients. However, there is more to the symbiosis, as it is also known to suppress losses to pathogens, provide drought and salt resistance, may increase soil aggregation and increase resistance to potentially toxic elements [23, 24]. The interactions of *biochar* with *arbuscular mycorrhizal fungi* depend on *biochar* type, application rate, soil type, crop type and are still under investigation.

Note: Although *biochar* may interact with many other soil microbes [25], *arbuscular mycorrhizal fungi* interactions are emphasized, since the majority of *biochar* research is focused on those.

21. aromaticity (of biochar)

The concept of spatial and electronic structure of cyclic molecular systems displaying the effects of cyclic electron delocalization which provide for their enhanced thermodynamic stability (relative to acyclic structural analogs) and tendency to retain the structural type in the course of chemical transformations. A quantitative assessment of the degree of aromaticity is given by the value of the resonance energy. It may also be evaluated by the energies of relevant isodesmic and homodesmotic reactions. Along with energetic criteria of aromaticity, important and complementary are also a structural criterion (the lesser the alternation of bond lengths in the rings, the greater is the aromaticity of the molecule) and a magnetic criterion (existence of the diamagnetic ring current induced in a conjugated cyclic molecule by an external magnetic field and manifested by an exaltation and anisotropy of magnetic susceptibility) [26].

Note: The extent to which the C in *biochar* has been transformed into energetically stable aromatic ring structures contributes decisively to both fate and reactivity of biochar in the environment [27].

See Biochar persistence.

22. available water

The amount of soil water per unit volume available to plants, calculated as the difference between *in situ field capacity* and the permanent *wilting point* [7].

Note: Available water in soil-*biochar* mixtures is not always increased by addition of biochar, as the outcome is contingent on the biochar application rate and the specific soil type. In *sandy soils, biochar* is able to reduce permanent *wilting points* and increase the amount of water available at all levels of water content [28].

See field capacity.

23. binary adsorption system

A multi-component system with two types of adsorbates.

See adsorption, adsorbate.

24. binding site

A specific region (atom, functional group) on the external surface or pore walls of *biochar* that is capable of entering into an interaction with an *adsorbate* [29].

25. biochar

A solid, multi-functional, porous carbonaceous product of agricultural *biomass pyrolysis* in the temperature range of 350 to 1000 °C in the absence of or under limited oxygen. The initial feedstock properties and processing conditions (heating rate, final pyrolysis temperature, residence time, *pyrolysis* equipment type) largely control the yield and physicochemical properties of *biochar*. The hydrogen-to-organic carbon (H/C_{org}) and oxygen-to-organic carbon (O/C_{org}) ratios of the as-prepared *biochar* should be below 0.7 and below 0.4, respectively. *Biochar* is used in a wide range of applications, including but not limited to soil conditioning and remediation, anaerobic digestion of organic wastes, composting, potable water and wastewater treatment, as an additive to animal feed and in composite building materials.

26. biochar-based catalyst

An *engineered biochar* where *biochar* acts as an eco-friendly and versatile catalyst support for applications in areas such as soil remediation, water filtration, chemical synthesis, biofuel production, and catalytic degradation of pollutants [30].

27. biochar half-life ($t_{1/2}$)

The time required for *biochar* to decompose to half of its original quantity [31], under environmental (temperature, moisture, microorganisms) and other conditions related to the specific biochar application.

28. biochar amendment

See biochar soil amendment.

29. biochar charging

The process of adding macro- and micro-nutrients to *biochar* before soil application. Commonly, this is achieved by mixing it with urine, compost, and manure from livestock.

Note: Not to be confused with *biochar* activation, typically used to describe the high temperature process of increasing the *porosity* of carbonaceous materials by using steam, carbon dioxide, or inorganic salts.

See biochar inoculation.

30. biochar-coated seeds

Seeds covered in *biochar* particles. Using *biochar-coated seeds*, increases the retention of water and nutrients around the seeds and surrounding soil. Coating the seeds prior to planting can dramatically reduce the need for high frequency saturation watering in the period immediately following planting and can also increase plant growth and sustain plant life [32].

31. biochar composite

The product of *biochar* and one or more additives, with the purpose of combining the advantageous properties of each material and consequently achieving better performance in a specific application.

32. biochar inoculation

The process of adding beneficial aerobic microbes and other microorganisms to the biochar surface and pores.

Note: Not to be confused with *biochar* activation, typically used to describe the high temperature process of increasing the *porosity* of carbonaceous materials by using steam, carbon dioxide or inorganic salts.

See biochar charging, enriched biochar.

33. biochar soil amendment

The application of *biochar* to a soil with the intention to improve one or more soil properties, functions, or ecosystem services such as carbon sequestration.

See soil carbon sequestration.

34. biochar persistence

The duration that *biochar* remains in the environment in its original form, typically measured as half-life or *mean residence time. Biochar* persistence is a result of both the molecular composition of the *biochar* material itself as well as the environmental conditions, such as soil climate and composition (texture, mineral, and mineralogy composition), content of plant-derived organic matter, and microbial population composition [33]. The upper H/C_{org} limit of 0.7 is imposed to assure abundant fused aromatic ring structures and to distinguish *biochar* from the raw feedstocks or from other materials which are only partially or deficiently carbonized [34].

Note: Persistence does not mean that *biochar* is stationary: *biochar* may still move through the soil or in aquifers without being decomposed, oxidized, or mineralized [33].

35. biochar pH

The numeric value expressing the pH of a 1:10 w/v *biochar*/distilled water solution after mechanical shaking for 1 h at 25 °C and allowing the suspension to stand for 30 min [35]. Most ligno-cellulosic *biomasses* result in alkaline *biochars*, although acid and/or neutral *biochars* are occasionally reported [36].

See soil pH.

36. biochar sustainability policy

A framework comprising a set of concepts, commitments and action plans toward optimizing environmental, societal and economic aspects of *biochar* production and application, as agreed between all interested parties (society, industry, and government) [31]. This policy forms part of the *European Biochar Certificate*.

See European Biochar Certificate, International Biochar Initiative (IBI) Certification Program.

37. biocoal

The product of *biomass torrefaction*. Not to be confused with *biochar*, since *biocoal* is exclusively used as an energy source. Compared to the raw *biomass*, *biocoal* has the advantages of improved energy density, more homogeneous composition, increased hydrophobicity and grindability [37].

See torrefaction (of biomass).

38. biomass

Material produced by the growth of microorganisms, plants, or animals [38].

39. biotic stress

The negative impact on plants, trees and beneficial microorganism populations in soil, caused by other living organisms, including fungi, bacteria, viruses, parasites, weeds, insects, and other native or cultivated plants [39, 40].

See abiotic stress.

40. black carbon

The *pyrogenic carbon* materials dispersed in the environment from wildfires and fossil fuel combustion [39]. The term should be taken to refer to the entire material, not just the fused ring fraction or the C atom. The use of this term is discouraged (or should be used only if absolutely necessary and in the context described here), to avoid confusion with "Black C". "Black C" spelled with "C" and not "carbon" refers to the C atom, and not to the material that also contains H, O, N, and ash minerals. Black carbon should also not be confused with "carbon black", which is an industrially manufactured colloidal carbon material in the form of spheres and of their fused aggregates with sizes below 1000 nm [41].

41. boundary layer

The stagnant region (film) around the *adsorbent* where properties vary from that in the bulk fluid.

42. boundary layer diffusion

See film diffusion transport.

43. Boyd's model

A diffusion-based model for *adsorption kinetics* analysis that assumes that the key resistance to *adsorption* resides in the *boundary layer* surrounding the *adsorbent*. In Boyd's model, the boundary condition requires the adsorbed concentration to be constant and equal to the adsorbed concentration at equilibrium [20, 42]. The external diffusion processes were characterized by the time dependence $-\log(1-F)$, where *F* is the equilibrium degree in the system calculated by the following equation:

$$F = \frac{q_t}{q_e}$$

where q_t is the adsorbed substance amount per sorbent mass unit at the moment of time t, and q_e the adsorbed substance amount per sorbent mass unit in the equilibrium state ($q_e \text{ mg g}^{-1}$). The *sorption* limitation by intradiffusion processes was determined by the $F - B_t$ dependence, where B_t is the dimensionless Boyd parameter (t corresponds to time) calculated by the following equation:

$$B_t = 0.4977 - \ln{(1-F)}$$

See adsorption.

44. buffering capacity (soil)

The ability of solid phase soil materials to resist changes in ion concentration in the aqueous solution phase. Can be expressed as $\Delta C_s / \Delta C_1$ where C_s represents the concentration of ions on the solid phase in equilibrium with C_1 , the concentration of ions in the liquid solution phase. Includes pH buffering as well as the buffering of other ionic and molecular components [7]. The buffering capacity is affected by the presence and types of clay, organic matter and other colloidal constituents [35]. Some *biochars* may act as a short-term pH buffer.

See soil pH.

45. bulk density

The dry mass of soil or *biochar* per unit bulk volume. The bulk volume is determined before the sample (soil, *biochar*, or soil plus *biochar*) is dried.

46. **bulk solution transport**

The movement of the *adsorbate* through the bulk liquid to the *boundary layer* of fixed film of liquid surrounding the *adsorbent* [43].

47. capillary condensation

In porous solids, it is the process of multilayer *adsorption* as vapor proceeds to the point at which pore spaces are filled with liquid separated from the gas phase by menisci. The concept loses its sense when the dimensions of the pores are so small that the term meniscus ceases to have a physical significance [44].

48. carbon abatement

The reduction of the amount of carbon dioxide that results from some action, process or intervention. For example, in a slow *pyrolysis*-based *biochar* production system, a carbon abatement equivalent to 0.76 ton of CO₂ per ton of feedstock processed was achieved under a conservative soil half-life of 240 years and 29 % *biochar* mass yield [45, 46].

See climate change mitigation, carbon footprint.

49. carbon cycle

The sequence of transformations whereby carbon dioxide is fixed in living organisms by photosynthesis or by chemosynthesis, liberated by respiration and by the death and decomposition of the fixing organism, or used by heterotrophic species, and ultimately returned to its original state.

50. carbon footprint

A quantification of the *greenhouse gas (GHG) emissions* during the life cycle of the product. It is being increasingly applied for multiple purposes, such as: to communicate the carbon footprint to customers, to facilitate the development and implementation of GHG management strategies across product life cycles, to identify potential opportunities for GHG mitigation along the supply chain, to track performance and progress in reducing GHG emissions over time and to assist the consumer in the selection of products with the least climate change impact [47].

See carbon abatement, greenhouse gas (GHG) emissions, climate change mitigation.

51. carbon storage (carbon stock)

The quantity of carbon held within a "pool" at a specific time, meaning a reservoir or system which has the capacity to accumulate or release carbon [48].

Note: examples of carbon pools are living *biomass* (including above and below ground *biomass*), dead organic matter (including dead wood and litter) and soils.

See carbon abatement, climate change mitigation.

52. carbon capture

The process of capturing carbon dioxide (CO_2) emissions to reduce the amounts of CO_2 entering the atmosphere and to minimize the associated global warming and ocean acidification effects [49].

See carbon abatement, climate change mitigation.

53. cation exchange capacity

The maximum number of moles of adsorbed positive charge that can be desorbed from unit mass of a material under given conditions of temperature, pressure, solution composition, and material-solution mass ratio [50]. Expressed in millimoles of charge per kilogram (mmol(+) kg⁻¹) of material.

54. cellulose

A linear polysaccharide consisting of monomeric units of anhydro-D-glucose units. *Cellulose* is a major component of lignocellulosic *biomass*, along with *hemi-cellulose* and *lignin*. The *pyrolysis* of *cellulose* mainly occurs between 315 and 400 °C [51, 52].

See lignin, hemi-cellulose.

55. chemical activation (of *biochar*)

The treatment of *biochar* with a chemical activation agent (*e.g.*, potassium hydroxide, phosphoric acid, or zinc chloride), followed by heating at a temperature of 450 to 700 °C in an activation kiln in order to increase its *porosity*. The activated *biochar* is then washed with water to remove the residues from the activation agent. The filtrate is passed to a chemical recovery unit for recycling [53].

See physical activation (of biochar).

56. chemical adsorption

See chemisorption.

57. chemisorption

Adsorption which results from chemical bond formation (strong interaction) between the *adsorbent* and the *adsorbate* in a monolayer on the surface [54].

See adsorption, adsorbate, adsorbent.

58. circular economy

A model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended.

Note: Circular bio-economy encompasses the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products, and bioenergy [55].

59. clayey soil

(i) Texture group consisting of sandy clay, silty clay, and clay soil textures. (ii) Family particle-size class for soils with 35 % or more clay and below 35 % rock fragments in upper subsoil horizons [7].

See soil texture, soil separates.

60. climate change mitigation

A human intervention to reduce the sources or enhance the sinks of greenhouse gases.

Note: Climate change mitigation policies also include human interventions to reduce the sources of other substances which may contribute directly or indirectly to limiting climate change, including, for example, the reduction of particulate matter (PM) emissions that can directly alter the radiation balance (*e.g.*, black carbon) or measures that control emissions of carbon monoxide, nitrogen oxides (NO_x), volatile organic compounds (VOCs), and other pollutants that can alter the concentration of tropospheric ozone (O_3) which has an indirect effect on the climate [56].

See carbon abatement, greenhouse gas (GHG) emissions.

61. climate smart agriculture (CSA)

An approach to developing the technical, policy, and investment conditions to achieve sustainable agricultural development for food security under climate change. CSA integrates the three dimensions of sustainable development (economic, social, and environmental) by jointly addressing food security and climate challenges [57]. It is composed of three main pillars:

- 1. sustainably increasing agricultural productivity and incomes
- 2. adapting and building resilience to climate change
- 3. reducing and/or removing greenhouse gases emissions, where possible

See carbon abatement, greenhouse gas (GHG) emissions.

62. competitive adsorption

The solute-solute competition for active adsorption sites on biochar in multi-component systems [58].

See adsorption, adsorbate, adsorbent.

63. complexation

Formation of multi-atom structures with specific metal-ligand interactions which include chelation and coordination. It may be surface (outer) or inner sphere *complexation* [19].

Note 1: The binding mechanism depends on the affinity of the metals to the ligands on the surface of the *biochar* and this is the case for transition metals with partially filled *d*-orbitals [59].

Note 2: Oxygen-containing *functional groups* on the surface/pores of *biochar* are effective at binding metals via *complexation* and is generally true for *biochar* from low temperature *pyrolysis* [19].

See chemisorption.

64. contaminant immobilization

The process of using *biochar* to reduce the mobility of harmful and toxic mobile *adsorbates* (contaminants) as part of *environmental remediation* measures.

See environmental remediation, adsorption.

65. **C** π -cation interactions

Electrostatic interactions between the aromatic rings of carbonaceous materials (*adsorbent*) and cations (*adsorbate*) [11].

66. dark earth soil

See Terra Preta soil.

67. **decolorization** (by using *biochar*)

Color removal via *adsorption* and/or catalytic degradation by *biochar* of color-laden wastewaters or effluents principally from dyeing operations and tannery and Kraft bleaching processes.

68. desertification

Land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities [60]. It is accompanied by a reduction in the natural potential and fertility of the land and a decrease in surface and ground water resources.

See soil erosion.

69. designer biochar

See engineered biochar, functionalized biochar.

70. desorption

A phenomenon in which a substance in an adsorbed state is released from the bulk or surface of a material. It is the opposite of *adsorption* [61].

See adsorption, adsorbate, adsorbent.

71. dipole-dipole H-bonding

Occurs between the hydroxyl or amine groups (H-donor) of the *biochar's* surface and electronegative atoms such as O and F in the *adsorbate* structure [62].

72. Dubinin-Radushkevich (DR) isotherm

An *adsorption isotherm* that factors in the effect by the porous structure of the *adsorbent* and generally expresses the *adsorption mechanism* with a Gaussian energy distribution onto heterogeneous surfaces [63, 64].

$$q_{\rm e} = q_{\rm DR} {\rm e}^{-K_{\rm DR} \varepsilon^2}$$

$$\ln q_{\rm e} = -K_{\rm DR}\varepsilon^2 + \ln q_{\rm DR}$$

where

$$\varepsilon = RT \ln\left(\frac{C_{\rm s}}{C_{\rm e}}\right)$$

 $q_{\rm e}$, mg g⁻¹, is the *adsorption capacity* of *biochar* at equilibrium with the *adsorbate* (the subscript e stands for equilibrium).

 $q_{\rm DR}$, mg g⁻¹, is the theoretical isotherm saturation capacity; $K_{\rm DR}$, mol² kJ⁻², is a constant related to *sorption* energy; ε , J mol⁻¹, is the Polanyi potential; $C_{\rm s}$, mg L⁻¹, is the saturation solubility mass concentration; $C_{\rm e}$, mg L⁻¹, is the equilibrium mass concentration of *adsorbate*; R, J mol⁻¹ K⁻¹, is the gas constant; and T, K, is the temperature.

Note 1: Normally fits well for *adsorption* systems with high solute activities and intermediate concentration ranges.

Note 2: The magnitude of ε can facilitate distinguishing between *physical* (less than 8 kJ mol⁻¹), ion exchange (8– 16 kJ mol⁻¹) and *chemical adsorption* (exceeds 16 kJ mol⁻¹) for the system under consideration [22, 63].

Note 3: For aqueous adsorption, as saturation solubility mass concentration of the absorbate is much higher than equilibrium mass concentration, the term (C_s/C_e) can be approximated to.

$$\left(1+\frac{C_{\rm s}}{C_{\rm e}}\right)$$
 or $\left(1+\frac{1}{\frac{C_{\rm e}}{C_{\rm s}}}\right)$

Renaming the dimensionless variable C_e/C_s as C, the Polanyi potential in the DR isotherm can be shown as.

$$\varepsilon = RT \ln \left(1 + \frac{1}{C} \right)$$

See adsorption, adsorbate, adsorbent.

73. electrical conductivity (EC)

The capacity of a soil-solution mixture or material to conduct or transmit electrical current. In soil and *biochar* samples it is related to the *functional groups* and potential electrolyte substances released in water after stirring for a fixed period of time [65].

See functional group.

74. electrostatic interaction

The attractive or repulsive interaction between the electric charges on an adsorbate and those present on biochar.

Note 1: It is highly dependent on the point of zero net charge (PZNC) of biochar and pH of the solution [66].

Note 2: The interactive strength is usually less than 50 kJ mol⁻¹.

75. Elovich equation

An empirical equation in *adsorption kinetics* suited for heterogeneous adsorbing surfaces and employed in fitting *chemical adsorption* data.

$$q_t = \frac{1}{\beta} \ln\left(1 + \alpha\beta t\right)$$

where q_t , mg g⁻¹, is the amount adsorbed at time t; α , mg g⁻¹ min⁻¹, is the initial rate constant; β , g mg⁻¹, is the *desorption* constant; and t, min, is the time.

Note: Linearizing for easy computation, an assumption of $\alpha\beta t >> 1$ is made [67].

See adsorption, adsorbate, adsorbent.

76. eluent

See regenerant.

77. engineered biochar

Biochar that had its physicochemical and/or textural properties purposedly tuned during *biomass pyrolysis* or through post-production physical and chemical processes [68]. The term used to describe application-specific, outcome-based *biochar* production and/or modification.

See biochar inoculation, biochar charging.

78. enriched biochar

An *engineered biochar* embedded with inorganic or organic substances. The aim is to produce *biochar* with specific physicochemical properties and improved performance for a specific application [31, 69, 70].

See biochar charging, engineered biochar, biochar inoculation.

79. environmental remediation

The removal of pollution or contaminants from environmental media such as soil, groundwater, sediment, or surface water. *Biochar* has been widely used in environmental remediation and has proven to be effective in removing organic and inorganic contaminants through *adsorption* and other mechanisms [27, 71].

80. enthalpy (of pyrolysis)

The energy required to raise *biomass* from room temperature to the reaction temperature and convert the solid *biomass* into the reaction products of gas, liquids, and *biochar*. The average value of the enthalpy for *pyrolysis* for each kg of the *biomass* tested is approximately 1.5 MJ when the *biomass* has typical moisture content of 8–10 %. The values for the woody *biomass* are higher than those of the herbaceous materials [72].

See pyrolysis (of biomass).

81. European Biochar Certificate (EBC)

A voluntary *biochar* industry standard in Europe describing essential *biochar* physicochemical analyses that should be performed and setting limit values to categorize *biochar* into the following four categories: EBC-Feed (Class I), EBC-AgroBio (Class II), EBC-Agro (Class III), and EBC-Material (Class IV). The *European Biochar Certificate* aims to enable and guarantee sustainable *biochar* production. It was introduced to give *biochar* users (*e.g.,* farmers) a reliable quality basis, while giving producers the opportunity of proving that their product meets well-defined quality standards. It further aims to provide a firm state-of-the-art knowledge transfer as a sound basis for future legislation. Finally, it was introduced to prevent and hinder misuse or dangers from the initial *biomass* harvesting (or collection) such as cutting down native forests to produce *biochar* [65].

See International Biochar Initiative (IBI) Certification Program.

82. external mass transfer

See film diffusion transport.

83. film diffusion transport

The transport by diffusion of the *adsorbate* through the fixed (stagnant) liquid film surrounding the *adsorbent* to the entrance of the pores of the *adsorbent* [20].

84. field capacity (FC)

The content of water, on a mass or volume basis, remaining in a soil 2 days after having been wetted with water after prolonged rainfall or irrigation, and after free gravitational drainage is negligible [7]. *Biochar* effects on FC varies with feedstock selection, *pyrolysis* temperature and soil type.

85. flammability (of biochar)

A flammable *biochar* is any *biochar* that is combustible or may contribute to a fire through friction or brief contact with a source of ignition. The flammability of *biochar* is measured according to the UN Manual of Tests and Criteria, part III N, 1 Test for readily combustible solids [73].

86. food security

A situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life [74]. The application of *biochar* to degraded soils may help toward this purpose.

See climate change mitigation.

87. Freundlich isotherm

An empirical equation proposed by Freundlich in 1907 for describing *adsorption* characteristics of heterogeneous surfaces.

$$q_{\rm e} = K_{\rm F} C_{\rm e}^{\frac{1}{n}}$$

where q_e , mg g⁻¹, is the amount of *adsorbate* adsorbed per unit weight of *adsorbent*; $K_{\rm F}$ (mg g⁻¹) (L mg⁻¹)^{1/n}, is the Freundlich constant; 1/n is the Freundlich intensity parameter, dimensionless; and C_e , mg L⁻¹, is the equilibrium amount of *adsorbate*.

Note: 1/n describes the magnitude of the *adsorption* driving force and predicts *adsorption* to be irreversible, favorable, linear, and unfavorable when values of 1/n = 0, 1/n < 1, 1/n = 1, and 1/n > 1, respectively [17, 63].

See adsorption, adsorbate, adsorbent.

88. functional group

An atom or a group of atoms that has similar chemical properties whenever it occurs in different compounds. It defines the characteristic physical and chemical properties of families of organic compounds [75].

89. functionalized biochar

See engineered biochar.

90. gasification (of biomass)

The thermochemical conversion of solid/liquid organic compounds to a gas/vapor phase and a solid phase by heating the material at high temperatures (above 700 °C), without combustion, with a controlled amount of oxygen and/or steam. The gas phase has a high heating power and can be used for power generation or biofuel production. The solid phase includes the organic unconverted fraction and the inert material present in the treated *biomass* [76, 77].

91. greenhouse gas (GHG) emissions

Gases that trap emanated heat in the atmosphere are called *greenhouse gases*. These include but are not limited to the following: carbon dioxide, methane, nitrous oxide, and fluorinated gases. The primary sources of *greenhouse gas emissions* are transportation, electricity production, heavy industry, commercial and residential activity, and agriculture.

See carbon abatement, climate smart agriculture (CSA).

92. hemi-cellulose

A branched polysaccharide comprised of different sugar monomers such as glucose, xylose, mannose, galactose arabinose, glucuronic, and galacturonic acid. *Hemi-cellulose* is a major component of lignocellulosic *biomass*, along with *cellulose* and *lignin*. During *pyrolysis*, it readily degrades within the temperature range of 220–315 °C [51, 52].

See *cellulose*, *lignin*.

93. hydrochar

The solid product of *hydrothermal carbonization* (HTC) or *liquefaction* (sometimes referred to as HTC material), and is distinct from *biochar* due to its production process and properties [78]. It typically has higher H/C ratios [79] and lower aromaticity than *biochar* as well as little or no fused aromatic ring structures [31].

See hydrothermal carbonization (HTC).

94. hydrothermal carbonization (HTC)

The treatment of *biomass* or any biodegradable waste with water at a temperature in the range of 100–374 °C in a closed reactor at a pressure that maintains water in the liquid state (as defined by the volume of the reactor and the thermodynamic properties of water in this temperature range). The result is a solid product with increased carbon content (*hydrochar*) and the residual water, referred to as HTC wastewater.

See hydrochar.

95. International Biochar Initiative (IBI) Certification Program

A voluntary scheme administered by the International Biochar Initiative to provide certification of *biochar* products. The purpose of the program is to provide to *biochar* manufacturers the opportunity to demonstrate that their *biochar* (*s*) meet the minimum criteria established in the latest IBI Biochar Standards. Currently, the IBI standards apply to *biochar* produced in North America.

See European Biochar Certificate.

96. intra-particle diffusion

The transport of the *adsorbate* through the pores by a combination of molecular diffusion through the pore liquid and/or by diffusion along the surface of the *adsorbent*.

97. intra-particle diffusion model

See Weber and Morris intra-particle diffusion model (IPD).

98. ion exchange

The exchange of cations and anions on *biochar* surface with dissolved species in the liquid phase.

Note: For metallic *adsorbates,* substitution or exchanges are more likely to occur with other metallic elements within groups 1–3 of the periodic table due to similar bond characteristics following the Goldschmidt geochemical classification [80].

99. ionic strength

On a molality basis,

$$I_m = \frac{1}{2} \sum m_{\rm B} z_{\rm B}^2$$

where the sum goes over all the ions B, and *m* denotes the molality of ion B, z_B is the charge number of ion B [81]. The ionic strength on a concentration basis is defined analogously

$$I_{\rm c} = \frac{1}{2} \sum c_{\rm B} z_{\rm B}^2$$

where *c* denotes the amount concentration of ion B.

100. isoelectric point (IEP)

The pH value at which the net electric charge of an elementary entity is zero [82].

101. labile carbon

Soil organic matter in transition from fresh residues to CO₂ or inert C. Much of it consists of recently incorporated plant, faunal, and microbial debris, with a turnover time of less than a decade [83].

See soil organic matter (SOM).

102. Langmuir isotherm

A hyperbolic equation based on assumptions of *adsorption* reversibility, monolayer coverage of *adsorbent*'s surface, homogeneous surface, existence of a fixed number of accessible sites on *adsorbent*, and non-existence of *adsorbate–adsorbate* interactions.

$$q_{\rm e} = \frac{q_m K_{\rm L} C_{\rm e}}{1 + K_{\rm L} C_{\rm e}}$$

A dimensionless factor, separation factor, $R_{\rm L}$, is expressed as.

$$R_{\rm L} = \frac{1}{1 + K_{\rm L}C_{\rm o}}$$

where q_e , mg g⁻¹, is the amount of *adsorbate* adsorbed per unit weight of *adsorbent* at equilibrium; q_m , mg g⁻¹, is the maximum *adsorption capacity* of the *adsorbent*; K_L , L mg⁻¹, is the Langmuir constant related to the affinity between *adsorbate* and *adsorbent*; C_e , mg L⁻¹, is the equilibrium concentration of *adsorbate*; and C_o , mg L⁻¹, is the initial *adsorbate* mass concentration.

Note: R_L is calculated only if the experimental data is well fitted by the *Langmuir isotherm* and is interpreted as irreversible, favorable, linear, and unfavorable *adsorption* when $R_L = 0$, $0 < R_L < 1$, $R_L = 1$, and $R_L > 1$ respectively [19, 63].

See adsorption, adsorbate, adsorbent.

103. Lagergren pseudo-first order kinetics model (PFO)

A two parameter, reaction-based, exponential rise to the maximum rate model for fitting kinetic data on *adsorption*.

$$q_t = q_{\rm e} \left(1 - {\rm e}^{-k_1 t}\right)$$

where q_t and q_e , mg g⁻¹, are the amount of adsorbed *adsorbate* at time *t* and at equilibrium respectively; k_1 , min⁻¹, is the rate constant; and *t*, min, is time.

Note: Often applies well for only the initial 20–30 min of *adsorption*. Deviation at longer time periods generally attributed to the *boundary layer* effect [84].

See adsorption, adsorbate, adsorbent.

104. Lagergren pseudo-second order kinetics model (PSO)

A two-parameter hyperbolic rate model that assumes *chemical adsorption* involving valence forces through electron sharing between *adsorbate* and *adsorbent* [85].

$$q_t = \frac{q_e^2 k_2 t}{1 + q_e k_2 t}$$

where q_e and q_t , mg g⁻¹, is the amount of adsorbed *adsorbate* at equilibrium and at variable time *t*, respectively; k_2 , g mg⁻¹ min⁻¹, is the pseudo-second order rate constant; and *t*, min, is time.

Note: Concomitant to PSO is the initial *adsorption* rate h, mg g⁻¹ min⁻¹, expressed as $h = k_2 q_e^2$ [86].

See adsorption, adsorbate, adsorbent.

105. lignin

An organic polymer, composed of phenolic propylbenzene skeletal units, linked at various sites and apparently randomly [36]. A major component of lignocellulosic *biomass*, along with *cellulose* and *hemi-cellulose*. During *pyrolysis, lignin* slowly decomposes over the temperature range of 150–900 °C [51, 52, 87].

See cellulose, hemi-cellulose.

106. liming effect

The effect that a material delivers to acidic soils through increasing soil pH and reducing the solubility of aluminum and manganese, and through amending soil physical, physicochemical, chemical, and biological properties [88].

See soil pH.

107. liquefaction

A relatively low-temperature (300–400 °C), high-pressure (40–200 bar) process that produces bio-oil from a relatively wet *biomass* in the presence of a catalyst and hydrogen [89].

108. loamy soil

(i) Texture group consisting of coarse sandy loam, sandy loam, fine sandy loam, very fine sandy loam, loam, silt loam, silt, clay loam, sandy clay loam, and silty clay loam soil textures. (ii) Family particle-size class for soils with textures finer than very fine sandy loam but below 35 % clay and below 35 % rock fragments in upper subsoil horizons [7].

See soil texture, soil separates.

109. magnetic biochar

An *engineered biochar* that has undergone modification with magnetic precursors for the primary role of facilitating separation of powdered *biochar* grades from aqueous solution when exposed to a magnetic field [68].

Note: Magnetic modifications include co-*precipitation* approaches in alkaline Fe²⁺/Fe³⁺ solution, direct hydrolysis of Fe(NO₃)₃, oxidative hydrolysis/reduction, electro-modification, mechanochemical approaches, and co-*pyrolysis* of FeSO₄·7H₂O and *biomass*.

See engineered biochar.

110. macropores

In material and engineering sciences, *macropores* are the pores with a diameter exceeding 50 nm [90, 91]. In soil science, a class of pores with an equivalent diameter higher than 75 µm [92]. Very coarse *macropores* drain water very quickly and are responsible for preferential flows. *Macropores* are good for soil aeration.

See soil texture, soil separates.

111. mean residence time (MRT)

The average time for which biochar is present in soil and is determined as the inverse of the decay rate [30].

112. mesopores

In material and engineering sciences, *mesopores* are defined as having a diameter in the range of 2–50 nm [91, 93]. In soil science, a class of pores with the equivalent diameter between 30 and 75 μ m [94]. These pores contribute to capillary water flow and solute movement by advection and diffusion. The *mesopore* size is ideal to hold water that is easily available to plants.

See soil texture, soil separates.

113. micropore filling

The process in which molecules are adsorbed in the adsorption space within micropores [95].

See micropores.

114. micropores

In material and engineering science, *micropores* have a diameter of less than 2 nm [91, 96]. In soil science, a class of pores with the equivalent diameter between the range of 5–30 µm [92]. Pores smaller than 5 µm when not classified are also added to the *micropores*. The water within these pores drains very slowly and is not available to all plants. To enhance available water, *biochar* should ideally have pores larger than *micropores* and smaller than the larger *macropores* than drain water too quickly.

See soil texture, soil separates.

115. modified biochar

See engineered biochar.

116. monolayer adsorption

Adsorption in which all *adsorbate* molecules or ions are in contact with the surface layer of the *adsorbent* thus leading to a single layer of adsorbed species. Usually characteristic of *chemisorption* [94].

See adsorption.

117. monolayer adsorption capacity

The quantity of *adsorbate* molecules or ions needed to occupy all *adsorption sites* as determined by the structure of the *adsorbent* and by the chemical nature of the *adsorbate* for *chemisorption*.

Note: For *physisorption*, forming a complete monolayer of *adsorbate* in close-packed array while stating the kind of close packing explicitly when necessary is key [97].

See adsorption, adsorption capacity.

118. multi-component systems

Adsorption systems with more than one type of adsorbate.

See adsorption.

119. multilayer adsorption

Adsorption such that the *adsorption* space accommodates more than one layer of molecules, and not all adsorbed molecules are in contact with the surface layer of the *adsorbent* [98]. Normally typical of *physisorption* [94].

See adsorption, adsorbent, physisorption.

120. nanobiochar

Biochar having particle sizes below 100 nm, achieved through mechanical or thermal means [99, 100].

121. nucleophile– π^* interactions (n– π^* interactions)

Occurs between a nucleophile carbonyl oxygen (electron-pair donor) on the surface of the *adsorbent* (*biochar*) and the π electrons of the aromatic structures of the *adsorbate* [62].

122. nutrient availability (in soil)

The portion of any element or compound in the soil in chemical forms that can be readily taken up and assimilated by plants.

123. nutrient recycling

The reuse of collected or recovered nutrients in agriculture. It involves nutrient collection through the gathering of waste material including preliminary sorting and storage prior to a subsequent direct use or processing, and nutrient recovery through which a nutrient is extracted, purified, or concentrated from a substrate [101].

124. physical activation (of biochar)

The process of increasing the *porosity* of a carbonaceous material through the use of an oxidizing agent, such as steam, ozone, carbon dioxide, or air at temperatures usually above 700 °C [102]. These oxidizing agents penetrate into the internal structure of char and gasify the carbon atoms, which results in opening and widening of inaccessible pores.

See chemical activation (of biochar).

125. physical adsorption

See physisorption, adsorption.

126. physisorption

Adsorption in which the forces involved are intermolecular forces (van der Waals forces) of the same kind as those responsible for the imperfection of real gases and the condensation vapors, and which do not involve a significant change in the electronic orbital patterns of the species involved [103].

See *adsorption*.

127. **pi–pi interactions** (π – π interactions)

A phenomenon occurring between the π -electrons arising from the aromatic or aliphatic structures in *biochar* and the π -electrons of the aromatic rings of the *adsorbate* [63].

128. point of zero net charge (PZNC)

The condition of the solution for which the surface charge density of the *adsorbent* equals zero. It measures net surface charge (both internal and external) [19].

129. pore blocking

The obstruction to entry or exit of *adsorbates* in pores or capillaries with *pore width* comparable to the molecular size of the *adsorbate*. Pore blocking may also be a result of *capillary condensation* where the liquid-like phase in the pore of the *biochar* prevents entry or exit of *adsorbates*.

130. pore condensation

See capillary condensation.

131. pore diffusion

See intra-particle diffusion.

132. pore size

The distance between two opposite walls of the pore (diameter of cylindrical pores, width of slit-shaped pores). *Pore sizes* are classified as *micropores, mesopores*, and *macropores*.

See micropores, mesopores, macropores.

133. pore size distribution

The distribution of pore volume with respect to *pore size*; alternatively, it may be defined by the related distribution of pore area with respect to *pore size* [104].

See micropores, mesopores, macropores.

134. pore width

See pore size.

135. porosity

The total volume of pores and voids divided by the volume occupied by the solid [94].

136. precipitation

The formation of insoluble solids on the surface of *biochar* during *sorption* processes and as a result of the reaction between the *adsorbate* metallic ions with the mineral phases entrained in the *biochar*. *Precipitation* (under ambient conditions or elevated temperature and pressure) is also a common method through which various types of metal oxide nanoparticles are deposited on the *biochar* surface [105–107].

Note 1: Mineral phases include quartz (SiO₂), sylvite (KCl), calcite (CaCO₃), calcium anhydrite (CaSO₄), hydroxyapatite $Ca_{10}(PO_4)_6(OH)_2$, and may exist in free forms or intercalated within the carbon matrix of the *biochars* [15].

Note 2: Precipitation on *biochar* surfaces is highly likely for metals and rare earth metals with intermediate ionization potentials ranging from 2.5 to 9.5 and thus occurs more frequently on *biochars* from higher temperature *pyrolysis* since they generally possess higher alkalinity [42].

137. priming effect (of biochar)

An increase or decrease in mineralization of one source of organic matter (*e.g.*, native *soil organic matter*) due to the addition of a new organic matter source (*e.g.*, *biochar*) [31].

See soil organic matter (SOM).

138. pseudo-first order kinetics model

See Lagergren pseudo-first order kinetics model.

139. pseudo-second order kinetics model

See Lagergren pseudo-second order kinetics model.

140. pyrochar

See biochar.

141. pyrogenic carbon

"Pyrogenic C" (abbreviated to PyC after first use) is synonymous with black C. It should be used preferentially to "black C". PyC (or black C) refers to the (non-inorganic) C atoms that have undergone pyrogenic or thermal transformation, and by this definition only include C present in fused rings, including C on surfaces of fused aromatic C that may also bind to other atoms such as O and N, non-hydrogenated C, and hydrogenated C. The term does not include non-transformed C present in residual carbohydrates or lignin structures, or in tars, or in *functional groups* bound to fuse aromatic C such as carboxyl groups. Different methods to quantify PyC (or black C) typically attempt to capture this C fraction, but do so with varying success or intentionally capture a portion of it (*e.g.*, only the fused aromatic C without the surface C). When referring to a certain analytically-defined fraction, the method should be stated in conjunction with the term PyC [31].

See pyrogenic carbon capture and storage (PyCCS).

142. pyrogenic carbon capture and storage (pyccs)

A promising carbon sequestration technology that can mitigate climate change while improving soil fertility. The technological opportunities of PyCCS are represented by three tracks accounting for the sequestration of different *pyrolysis* products: *biochar* (as soil amendment), bio-oil (pumped into geological storages), and permanent-pyrogas (capture and storage of CO_2 from gas combustion) [108, 109].

See biochar, pyrogenic carbon.

143. pyrogenic organic matter

An umbrella term for all materials that are produced by thermochemical conversion and contain some organic C, such as charcoal, *biochar*, char, black carbon, soot, activated carbon, and may contain some or no *pyrogenic carbon* (PyC). The term refers to the material and not the C atom.

144. pyrolysis (of biomass)

Thermolysis (of *biomass*), usually associated with exposure to a high temperature in the absence, or limited concentration of oxygen [110].

Note 1: In the context of *biochar*, it is commonly defined as the thermochemical conversion of *biomass* to gas (a mixture of synthesis gas CO and H₂ and condensable volatile compounds), bio-oil and *biochar*, at temperatures in the range of 350 to 800 °C in an inert atmosphere.

Note 2: Pyrolysis is further categorized into fast and slow *pyrolysis*. Fast pyrolysis processes *biomass* in the temperature range of 600 to 1000 °C, heating rates between 10 and 10000 °C min⁻¹ and residence time in the range of several seconds. Slow *pyrolysis* processes *biomass* in the temperature range of 300 to 700 °C, heating rates between 0.1 and 10 °C min⁻¹ and residence times in the range of minutes to hours [111]. *Biochar* yield is favored in slow *pyrolysis* conditions.

See biomass, biochar.

145. quaternary adsorption system

A multi-component system with four different types of adsorbates.

See *adsorption*.

146. recalcitrance index

A temperature-programmed oxidation index to specifically evaluate the thermal oxidative stability of *biochar*. *The* recalcitrance index corresponds to relative stability as compared to graphite. It is calculated by dividing $T_{50,x,x}$ which is the temperature value corresponding to 50 % oxidation/volatilization of a *biochar* sample (named *x*), by $T_{50,graphite}$, an external standardization factor ($T_{50,graphite} = 885$ °C) [112].

147. Redlich-Peterson (RP) isotherm

A three-parameter *adsorption isotherm* equation that addresses the short-comings of *Langmuir* and *Freundlich isotherms* by incorporating both over wide *adsorbate* concentration ranges, applicable to heterogeneous and homogeneous systems [53].

$$q_{\rm e} = \frac{K_{\rm RP}C_{\rm e}}{1 + \alpha_{\rm RP}C_{\rm e}^g}$$

where q_e , mg g⁻¹, is the amount of *adsorbate* adsorbed per unit weight of *adsorbent* at equilibrium; K_{RP} , L g⁻¹, and α_{RP} , (mg L⁻¹)^{-g} are Redlich–Peterson constants and g (dimensionless) is an exponent with a value within 0 and 1.

Note: Redlich–Peterson isotherm translates into Henry's law when g = 0, into *Langmuir isotherm* when g = 1 and into *Freundlich isotherm* when g = 1 and $\alpha_{RP} >> 1$ [17, 113].

See adsorption, adsorbate, adsorbent.

148. regenerant

The substance or solution used to restore the adsorption capacity of spent biochar [50].

149. regeneration

The process used to recover the *adsorption capacity* of the *spent biochar* without repeating a *chemical* or *physical activation* step. It may include chemicals to oxidize the adsorbed material, steam to drive off the adsorbed material, solvents and biological conversion processes.

See adsorption, spent biochar.

150. regeneration agent

See regenerant.

151. regeneration cycles

The number of repeated *adsorption-desorption* cycles that *biochar* can be subjected to after which further usage as *adsorbent* will be economically unattractive as a result of decreased *adsorption capacity*.

152. regeneration solution

See regenerant.

153. sandy soil

(i) Texture group consisting of sand and loamy sand textures. (ii) Family particle-size class for soils with sand or loamy sand textures and below 35 % rock fragments in upper subsoil horizons [7].

See soil texture, soil separates.

154. seed coating (with biochar)

See biochar-coated seeds.

155. Sips isotherm

A hybrid equation featuring *Freundlich* and *Langmuir isotherms* for predicting heterogeneous *adsorption* systems and to bypass the limitation of *Freundlich isotherm* at higher *adsorbate* concentrations.

$$q_{\rm e} = \frac{K_{\rm s} C_{\rm e}^{\beta_{\rm s}}}{1 + \alpha_{\rm s} C_{\rm e}^{\beta_{\rm s}}}$$

where q_e , mg g⁻¹, is the equilibrium amount of *adsorbate* adsorbed per unit weight of *adsorbent K*_S, L g⁻¹, and α_S , L mg⁻¹, are the Sips isotherm model constants and β_S , dimensionless, is the isotherm model exponent.

Note 1: The *Sips isotherm* reduces to *Freundlich* and *Langmuir* at low and high *adsorbate* concentrations respectively.

Note 2: Operating conditions such as pH, temperature and concentration determine the outcome of the equation parameters [63].

See adsorption, adsorbate, adsorbent.

156. slash-and-char agriculture

A sustainable agricultural practice where vegetation is cleared and then charred on site to *biochar* rather than burnt to ash [114].

See biochar.

157. smart biochar

See engineered biochar, functionalized biochar.

158. soil aeration

The proportion of air-filled pores in the soil. The process by which air in the soil is replaced by air from the atmosphere. Depends largely on the structure of the medium, the volume and continuity of pores. Addition of *biochar* may increase soil aeration in certain soil types, mainly those with high clay content.

159. soil albedo

The fraction of the incident radiation that is reflected from the soil surface. Its value ranges from 0 to 1, where 0 represents a blackbody (theoretical medium) absorbing 100 % of the incident radiation. *Biochar* is close to a blackbody and will lower the albedo of bare soils to which it is applied as a power function with increasing *biochar* application rate, depending on soil moisture content and *biochar* application method [115].

160. soil bulk density

The mass of dry soil per unit of bulk volume, including the air space. The bulk density of most soils is reduced after *biochar* addition [116, 117].

161. soil carbon sequestration

Land management strategy that increases the soil organic carbon content, resulting in a net removal of CO₂ from the atmosphere [118].

See carbon storage (carbon stock), climate change mitigation, carbon abatement.

162. soil erosion

The movement and transport of soil by various agents, particularly water, wind, and mass movement. Factors such as rainfall intensity, rainfall volume, slope angle, soil properties, land use, and land management determine *soil erosion* rates. *Soil erosion* is reversible if certain soil protection and rehabilitation measures are taken. *Biochar* addition to weathered soils can help reduce soil losses, by improving their physical properties (such as aggregate stability) and increase erosion resistance [119, 120].

See desertification.

163. soil hydraulic conductivity

An expression of the readiness with which a liquid, such as water, flows through soil, in response to a given potential gradient. Represents the ability of a porous medium to conduct water. The effect of *biochar* on soil hydraulic properties depends on the feedstock and amount of *biochar* added and soil type including soil texture, aggregation, mineralogy. Contrasting results are found in the *biochar* studies [27, 117].

164. soil organic matter (SOM)

The sum total of all organic carbon-containing substances in soils. Chemically and physically, SOM consists of a mixture of plant and animal residues in various stages of decomposition and recombination, substances synthesized microbiologically and/or chemically from the breakdown products, and the bodies of live and dead microorganisms and small animals and their decomposing remains [121].

165. soil pH

The pH of a solution in equilibrium with soil. It is determined by means of a glass, quinhydrone, or other suitable electrode or indicator at a specified soil–solution ratio in a specified solution, usually distilled water, 0.01 M CaCl₂, or 1 M KCl [7, 52].

See acid soil, alkaline soil.

166. soil separates

The specific ranges of soil particle sizes. The smallest particles are clay particles and are classified as having diameters of less than 0.002 mm. Clay particles are plate-shaped instead of spherical, allowing for an increased specific surface area. The next smallest particles are silt particles and have diameters between 0.002 mm and 0.05 mm (in the United States Department of Agriculture (USDA) soil taxonomy). The largest particles are sand particles and are larger than 0.05 mm in diameter. Furthermore, large sand particles can be described as coarse, intermediate as medium, and the smaller as fine. Other countries have their own particle size classifications. Table 1 provides a comparison between the soil particle sizes as defined in the United States Department of Agriculture soil taxonomy and World Reference Base for Soil Resources (WRB).

Name of soil separate	Diameter limits (mm) (USDA classification)	Diameter limits (mm) (WRB classification)
Clay	<0.002	<0.002
Silt	0.002-0.05	0.002-0.063
Very fine sand	0.05-0.10	0.063–0.125
Fine sand	0.10-0.25	0.125–0.20
Medium sand	0.25-0.50	0.20-0.63
Coarse sand	0.50-1.00	0.63–1.25
Very coarse sand	1.00-2.00	1.25–2.00

Table 1: Soil separates and their diameters.

See soil texture.

167. soil texture

The relative proportions of the various *soil separates* in a soil as described by the 12 classes of *soil texture* [7]. The limits of the various classes are as follows:

Clay: Soil material that contains 40 % or more clay, below 45 % sand, and below 40 % silt.

Clay loam: Soil material that contains 27 to 40 % clay and 20 to 45 % sand.

Loam: Soil material that contains 7 to 27 % clay, 28 to 50 % silt, and below 52 % sand.

Loamy sand: Soil material that contains between 70 and 91 % sand and the percentage of silt plus 1.5 times the percentage of clay is 15 or more; and the percentage of silt plus twice the percentage of clay below 30 %.

Sand: Soil material that contains 85 % or more of sand; percentage of silt, plus 1.5 times the percentage of clay, shall not exceed 15.

Sandy clay: Soil material that contains 35 % or more clay and 45 % or more sand.

Sandy clay loam: Soil material that contains 20 to 35 % clay, 45 % sand.

Sandy loam: Soil material that contains 7 to 20 % clay, above 52 % sand, and the percentage of silt plus twice the percentage of clay is 30 or more; or below 7 % clay, below 50 % silt, and above 43 % sand.

Silt: Soil material that contains 80 % or more silt and below 12 % clay.

Silty clay: Soil material that contains 40 % or more clay and 40 % or more silt.

Silty clay loam: Soil material that contains 27 to 40 % clay and below 20 % sand.

Silt loam: Soil material that contains 50 % or more silt and 12 to 27 % clay (or) 50 to 80 % silt and below 12 % clay.

See soil separates, clayey soil, loamy soil, sandy soil.

168. sorption

The process by which a substance (sorbate) is sorbed (adsorbed or absorbed) on or in another substance (sorbent) [122]].

See absorption, adsorption.

169. spent biochar

The term given to *biochar* with an exhausted *adsorption capacity* and which requires *regenerative* or *reactivation* processes to recover its *adsorptive capacity*. This is the case where the *adsorbate*'s rate of *adsorption* onto and *desorption* off the *adsorbent* are in equilibrium [31].

See adsorption capacity, regeneration, regenerant.

170. tailor-made biochar

See engineered biochar, functionalized biochar, smart biochar.

171. Temkin isotherm model

An isotherm which accounts for *adsorbate-adsorbent* interactions and is characterized by the uniform distribution of binding energies up to some maximum value.

$$q_{\rm e} = \frac{RT}{b_{\rm T}} \ln \left(A_{\rm T} C_{\rm e} \right)$$

where q_e , mg g⁻¹, is the equilibrium amount of *adsorbate* adsorbed per unit weight of *adsorbent*; C_e is the equilibrium concentration of *adsorbate*, mg L⁻¹; A_T , L g⁻¹, is the Temkin isotherm equilibrium binding constant and b_T , J mol⁻¹, is the Temkin isotherm constant; R, J mol⁻¹ K⁻¹, is the universal gas constant; and T, K, is the temperature.

Note 1: Assumes a linear decrease in heat of *adsorption* of all molecules in the layer by ignoring extremely low and large *adsorbate* concentrations.

Note 2: Poor fits are usually obtained for complex *adsorption* systems with liquid-phase *adsorption* isotherms included [63].

See adsorption, adsorbate, adsorbent.

172. ternary adsorption system

A multi-component system with three different types of adsorbates.

See adsorption.

173. Terra Preta soil

Terra Preta (de Índio) is the local Portuguese name for a soil anthropogenically enriched by ancient indigenous cultures with nutrients and carbon that occurs, mainly, in some parts of the Amazon Basin, and literally means "Indian Black Earth." It commonly contains human artifacts (ceramics), moreover it is enriched with P, Ca, Sr, Ba, Mn, and *pyrogenic carbon* [123]. It is a source of inspiration and a model for some *biochar* research topics.

174. torrefaction (of biomass)

Thermochemical processing of *biomass* at atmospheric pressure, absence of oxygen and at temperatures typically between 200 and 320 °C. Torrefaction changes *biomass* properties to provide a better fuel quality for combustion and *gasification* applications. The final product is the remaining solid, dry, blackened material that is referred to as torrefied *biomass* or *biocoal*. Depending on the feedstock and required product quality excess heat can be generated for drying purposes or electricity production.

See biocoal.

175. water holding capacity

The ability of a soil to contain and to retain water. Dependent upon the factors, which determine hydraulic conductivity and permeability, *e.g.*, texture, organic matter, *porosity*, and interconnectedness of pores [124].

See field capacity.

176. Weber and Morris intra-particle diffusion model (IPD)

A diffusion-based single resistance rate model for the purposes of revealing the underlying rate determining step for *adsorption* onto solid *adsorbents*.

$$q_{\rm t} = k_{\rm p} t^{1/2} + C$$

where k_p , mg g⁻¹ min^{-1/2}, is the *intra-particle diffusion* rate constant; *C*, mg g⁻¹, is a constant that describes the thickness of the *boundary layer*.

Note 1: A zero value of *C* makes the *adsorption* rate fully pore diffusion controlled, otherwise *boundary layer* effect may be at play [125].

Note 2: Generally, multi-straight line regions arise upon application of IPD highlighting the mechanism of *adsorption* [20].

See adsorption, boundary layer.

177. wilting point

The mass of water per unit weight or per unit soil bulk volume in the soil, expressed in percent, that is held so tightly by the soil matrix that roots cannot absorb this water and a plant will wilt [126].

See field capacity, water holding capacity.

178. Yoshida H-bonding

Occurs between O and/or N-containing functional groups on the *biochar* surface and the aromatic rings of the *adsorbate* [62].

See adsorption.

3 Conclusions

The above list of terms related to biochar research is only the beginning of a dynamic document that aims to be enriched with further terms – and possibly refine the existing ones – in the future. Its objective is to become a reference document for students, researchers and any professional working with this material. If one term had to be singled out, the definition for the term "biochar" would be the one. Since biochar is a multi-functional material and biochar research is multi-disciplinary, it was important to develop an inclusive definition that is not bound to a specific application but covers all current applications and emerging future ones. This does not mean that biochar definitions provided elsewhere are not scientifically sound or complete. If a short and quick definition is required, this may come from the word biochar itself. The prefix "bio-" refers to a biomass-based material, whereas the suffix "-char" refers to the carbonization process of the biomass. Regardless of current and emerging applications, it is important to highlight that biochar production and applications should be environmentally sustainable. In this framework, biochar valorization strategies should involve negative emissions technologies (NET) that can remove carbon from the atmosphere and contribute to the reduction in greenhouse gases emission worldwide.

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List of abbreviations

Climate smart agriculture		
European Biochar Certificate		
Electrical conductivity		
Field capacity		
Greenhouse gas emissions		
Hydrothermal carbonization		
International Biochar Initiative		
Isoelectric point		
Weber and Morris intra-particle diffusion model		
Mean residence time		
Nitrogen oxides		
Lagergren pseudo-first order kinetics model		
Particulate matter		
Lagergren pseudo-second order kinetics model		
Pyrogenic carbon capture and storage		
Point of zero net charge		
Soil organic matter		
Volatile organic compounds		

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