Intelligent Agriculture
https://ojs.ukscip.com/index.php/ia/index

Review

Regenerative Biochar for Carbon Sequestration and Emerging Technologies in Soil Organic Carbon Management for Sustainable Agriculture: A Review

Annu Khatri , Krishan Kumar and Indu Shekhar Thakur *

Amity School of Earth & Environment Science, Amity University Haryana, Gurugram 122413, India
* Correspondence: isthakur@hotmail.com or isthakur@ggn.amity.edu

Received: 2 August 2025; **Revised:** 2 October 2025; **Accepted:** 13 October 2025; **Published:** 1 December 2025

Abstract: Climate change is one of the most serious environmental issues and immediate worldwide action is essential to safeguard the earth for future generations. This study examines the use of regenerative biochar in conjunction with machine learning to assess the potential of carbon in soil for climate smart agriculture. Biochar is cost effective, practical and environmentally benign and it may be used to efficiently sequester carbon dioxide, methane and nitrous oxide, all of which are significant Green House Gases. It is reasonably stable form of carbon, produced by pyrolizing biomass at both high and moderate temperatures. Biochar has been found to increase agricultural productivity, enhance nutrient and water efficiency and help the environment, in addition to assisting in carbon sequestration, gives a more productive choice for sustainable agriculture. It includes a vast range of applications, including construction materials like concrete and asphalt, innovative carbon-based composites, bioplastics, and even medical applications. The use of new artificial intelligence and machine learning technology contributed substantially to understanding climate change challenges without wasting time or money. This paper extensively covers all the regenerative biochar strategies for carbon sequestration and role of emerging technology in measuring and modelling soil organic carbon in agricultural lands.

Keywords: Biochar; Carbon Sequestration; Smart Agriculture; Agriculture Productivity; Machine Learning

1. Introduction

The rise in greenhouse gas emissions that causes global climate change is one of the most significant environmental problems. Most of these emissions are driven by human activities like forest loss and the burning of fossil fuels. The consequences have been dire; a notable increase in atmospheric CO_2 levels has contributed significantly to the rise in global temperatures. The average atmospheric CO_2 concentration worldwide increased from 279 parts per million during the preindustrial era to 412 parts per million in 2020 [1]. The productivity and quality of agriculture may be threatened by elevated atmospheric CO_2 levels linked to high soil carbon loss. In order to decrease the amount of gaseous carbon in the atmosphere and to encourage permanent soil carbon sequestration in order to build soil carbon stability, it is imperative that research be done and solutions be put into place that successfully lower carbon emissions. Therefore, the implementation of climate smart agriculture a combined strategy to sequester GHGs in order to boost productivity, encourage durability, mitigate climate change, and ease adaptation has been proposed [2].

Biochar is a solid material primarily derived from biomass, produced through pyrolysis, a thermochemical process conducted at high temperatures and low oxygen levels. Due to its unique physicochemical characteristics and interactions with soil processes, it has recently gained recognition as an effective soil amendment [3]. As the world moves toward the Fourth Industrial Revolution, technology is being integrated into every aspect of human activity. Remarkable advancements in technology, comparable to those seen in the First, Second, and Third Industrial Revolutions, are ushering humanity into a new era. Machine learning, in particular, has found applications across various areas of life, impacting both living conditions and costs. Its potential has also been explored in relation to biochar. In addition to reviewing machine learning and its connection to biochar, efforts have been made to apply machine learning to various aspects of biochar utilization [4]. The use of Information and Communication Technology (ICT) in agriculture has facilitated the development of Artificial Intelligence models that contribute to enhanced agricultural productivity. Biochar is produced from a variety of feedstocks, including wood residues, agricultural byproducts, animal waste, sewage sludge, and food waste, all of which are processed through pyrolysis at temperatures ranging from 350 °C to 750 °C. The characteristics of biochar depend on several factors, including the feedstock, hydrothermal treatment, duration of the treatment, and any pre- or post-pyrolysis processes [5]. As biochar gains recognition as a promising solution for mitigating climate change and enhancing soil carbon storage, there is an urgent need to address existing knowledge gaps and establish clear research objectives. Biochar has shown significant effects on plant functions, such as seed germination, growth, flowering, disease resistance, and stress adaptation. Studies indicate that biochar can boost plant yields by an average of 10% to 42% [6]. Additionally, crop residues left in agricultural fields can serve as an effective strategy for soil organic carbon storage and sequestration. Practices such as supporting cover crops and conservation tillage offer benefits like nutrient cycling, reduced surface water runoff, wind erosion control, and improved crop production [7]. Beyond its agronomic benefits, biochar plays a crucial role in mitigating climate change. When added to soil, biochar promotes long-term carbon sequestration, as its carbon remains in the soil one to two orders of magnitude longer than non-pyrolyzed organic waste [8]. This collective effort paves the way for biochar to be widely adopted as a sustainable solution in the fight against climate change [9]. Efficient methods for soil carbon sequestration are essential, and this paper thoroughly explores the regenerative strategies for carbon sequestration using biochar, along with the role of emerging technologies in measuring, modelling, and managing soil organic carbon in agricultural lands [10]. The systematic recycling of biochar in the environment has been depicted in **Figure 1** [11]. This paper extensively covers all of the regenerative biochar strategies for carbon sequestration and role of emerging technology in measuring, modelling and management of soil organic carbon in agricultural lands.

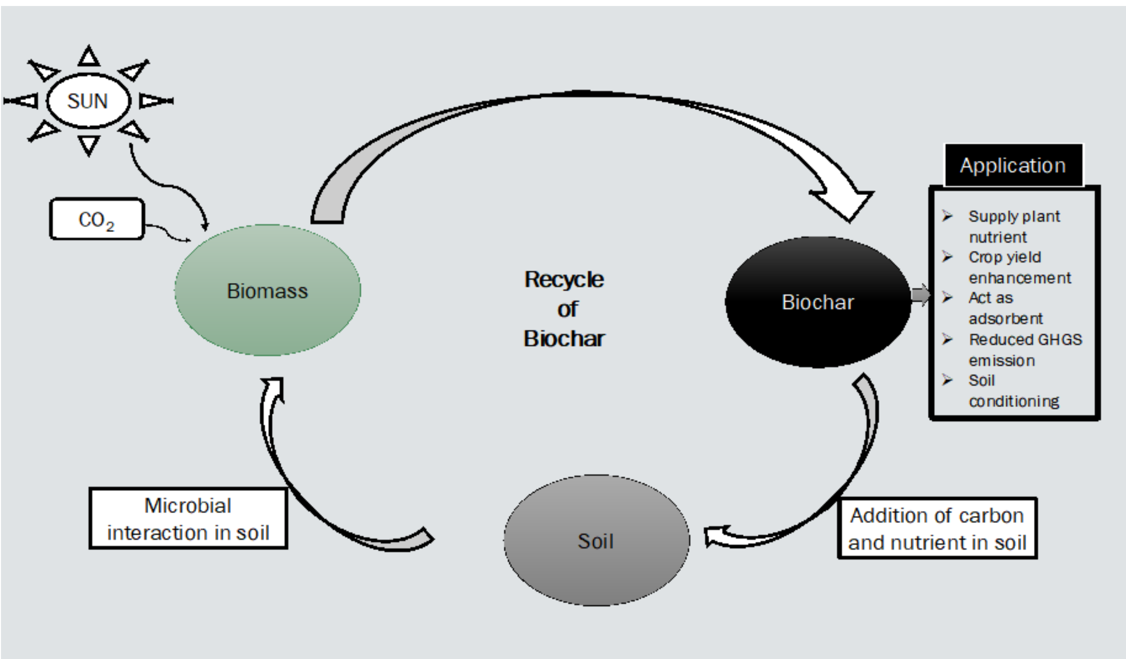

Figure 1. Systematic recycling of biochar in the environment.

2. Biochar Production Techniques

A rise in production of biochar has been prompted by a continuously increasing demand for utilizing in many different uses. Biochar may be generated using thermochemical conversion technology [12]. Pyrolysis, hydrothermal carbonization (HTC), gasification, Torre fractionation, and hydrothermal liquefaction are a few examples of thermochemical conversion processes. Various technologies for production of biomass are shown in **Figure 2** [13]. In order to make the best decision, the environmental and economic implications must be analysed. A strong argument develops when comparing the environmental and economic outcomes. However, only in rural Ethiopia, Kenya and Vietnam was a win situation for the environment and the economy (net market profits) recorded when the flame curtain kiln was deployed. There is a trade-off between the other flame curtain scenarios which involve producing biochar in rural China, Indonesia and Peru and the benefits to society's environment and the net market loss for the individual decision-maker (a company or a farmer). Even while Indonesia and Peru have relatively profitable flame curtain kiln places, the net economic loss in all countries is much higher per kilogram of trash when using gasifiers in metropolitan areas. The effects on the environment and the economy are therefore clearly trade-offs. Decision making is primarily influenced by the gasifier's comparatively high initial investment costs, labour and operational expenses, and alternative revenue streams [14].

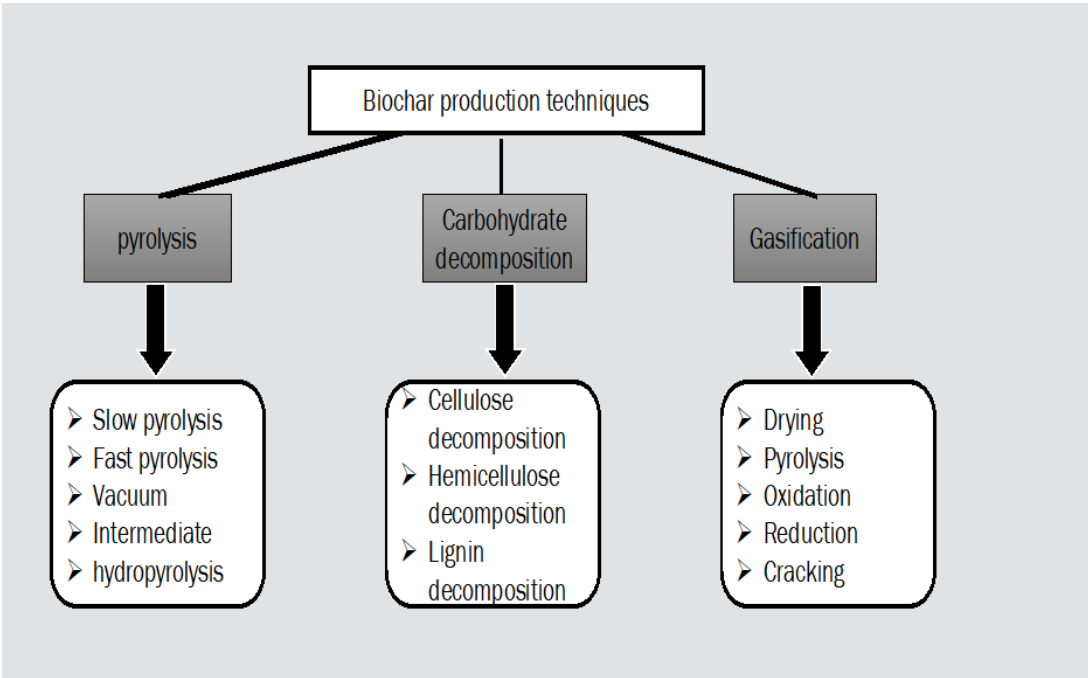

Figure 2. Different techniques for production of biomass.

2.1. Pyrolysis

Pyrolysis, a thermochemical process, is used to create syngas, biochar and bio-oil from fuel. After heating biomass to temperatures between 400 °C and 1,200 °C, it is utilized to thermally breakdown under anaerobic circumstances or in an oxygen poor environment (low stoichiometric oxygen atmosphere). It is a complex procedure that involves a wide variety of unique reactions in the reacting zone [15]. Another study shows pyrolysis was found to happen at low temperatures between 250 °C and 900 °C. In higher pyrolysis, heavy chemicals are broken down, converting the biomass into charcoal or gases [16]. The primary operational element affecting product efficiency is temperature. Biochar production decreases and syngas production increases as the pyrolysis temperature goes up [17]. Equation (1) indicates the gas yield, which includes all of the gases released throughout the process.

$$(C_6H_6O_6)_n \rightarrow (H_2 + CO + CH_4 + \ldots + C_5H_{12}) + (H_2O + CH_3OH + CH_3COOH + \ldots) + C \quad (1)$$

The second section of products' side shows a variety of liquid outputs, and final part shows solid output. Particularly, slow pyrolysis can be used to generate considerable quantities of biochar, whereas fast pyrolysis is more efficient at generating bio-oil [18]. As a result, the biochar field is leading as the most appropriate in many socioeconomic situations. We can create the biochar at all likely scales, ranging from the industrial to the residential level and even at individual farms. The potential for environmentally friendly production methods and multipurpose qualities in biochar make it a good fit for meeting the growing need in the areas of soil amendment, sustainable agriculture, environmental preservation, innovative materials, circular bio economy, and climate change mitigation. In addition to producing desired biochar materials, a portion of waste biomass that is readily available (such as agroforestry waste, biomass crops, agricultural residues, mill residues, animal manure, and many more) can be effectively used in pyrolysis to produce syngas, bio-oil, electricity, and process heat [19].

2.2. Types of Pyrolysis

Temperature, heating rate, and residence time are operating factors that influence pyrolysis. These operational parameters further divide pyrolysis into six distinct categories. Hydropyrolysis, flash pyrolysis, vacuum pyrolysis, slow pyrolysis, and quick pyrolysis are a few of these procedures. Each form of pyrolysis offers a few benefits and draw backs. In solid waste management, pyrolysis has several benefits, such as resource recovery, waste reduction, and energy production. However, there are limitations as well, including as complexity, complications with air pollution, the need to dispose of ash, and feedstock considerations. Pyrolysis in solid waste management can be used to minimise problems and maximise advantages with careful planning, investment, and compliance with regulations [20]. The characteristics of some biochars are furnished in **Table 1** [21].

Table 1. Characteristics of different types of biochar prepared from different natural raw materials and biomass.

Raw Material	Temperature (°C)	pH	SSA ($m^3\ g^{-1}$)	EC (ds cm^{-1})	Total C (%)	WHC (%)	CEC (cmol(p^+)kg^{-1})
Coconut shell	190–289	9.8	-	1.76	80.45	-	11.79
Rice husk	450–500	7.8	-	0.48	-	-	-
Cow dung	250–300	8.9	-	1.68	23.53	-	16.75
Corn cab	>600	9.7	186	0.0463	82.2	-	-
Green waste—leaves, twig	350,450,550	8.4	154	0.0018	75.4	-	-
Corn cob	650	9.6	187	0.0463	84.3	-	-
Water hyacinth	350	8.0	-	-	-	-	9.5
Cotton	450	-	0.2	-	-	-	-
Tobacco stalks	500	9.42	-	0.11	79	-	30
Oil palm fronds	500	6.55	-	0.21	42	-	-
Acacia wood	400	6.3		-			
Oil palm empty fruit bunches	500	8.9	-	0.41	67	-	-
Prosopis wood	450	8.7	-	2.2	-	-	9.76
Pinus radiata sawdust	700	9.7	795	0.0154	90	-	-
Oil palm trunk	500	9.8	-	0.18	57	-	-

3. Factors Affecting the Properties of Biochar

3.1. Feedstock

Biomass can be solid or liquid. Biomass is created when living or non-living organisms are used to produce organic, inorganic, and biological material. Woody biomass and non woody biomass are the two basic divisions of biomass. Wood biochar tends to be a great tool for recycling nutrients, particularly phosphorus and nitrogen into plant-available forms, and it performs exceptionally well in raising the amount of plant-available water content in soil. Ash content typically ranges from 1% to >50%, with higher values observed in manure and agricultural residues due to mineral enrichment. Increasing pyrolysis temperature generally increases ash content by concentrating inorganic constituents such as Ca, K, and Mg. Surface area is a critical property, typically ranging from 10 to 500 $m^2\ g^{-1}$, and may exceed 1,000 $m^2\ g^{-1}$ under activation conditions. Higher temperatures enhance pore development, leading to increased surface area and improved adsorption capacity. Feedstock composition significantly influences pore structure and surface functionality. Moisture content in biochar is generally low (<10%) but varies with storage and environmental conditions. Excess moisture can occupy pore spaces and reduce adsorption efficiency. Low moisture content improves biochar stability, handling, and performance in environmental applications. Overall, ash content, surface area, and moisture are key parameters governing biochar reactivity and application potential. Over time, the overall benefits of applying biochar shift from being abiotic to being biotic since many of its physical features vanish as it decomposes, but it can strengthen the microbial communities in the soil that are essential to soil fertility. In the area of soil, nutrient, and energy management, wood biochar thus represents unrealized promise because global climate change generates a variety of conditions that harm forest cover [22]. As determined by one study, there is a direct relationship between the initial sample moisture content and the surface chemistry of the generated charcoal contrasting the charcoals produced by pyrolysis using samples of hard and softwood bark [23].

3.2. Residence Time

Residence (pyrolysis time), which is more pronounced at lower temperatures, has been demonstrated to influence the amount of biochar generated as well as the degree of feedstock carbonization. Increased pyrolysis residence time results in higher levels of carbonization, which minimizes the amount of potentially dangerous organic matter and lessen the susceptibility of the biochar to microbial assault [24].

3.3. Biomass Pre-Treatment

It is well known that the properties of biochar are influenced by the pre-treatment of biomass before pyrolysis. Physical, physiochemical/thermal, chemical, and biological pre-treatments fall under these four broad categories. Because of the study, the pore size and total pore volume of rice residue biochars are related to their surface area; that is, the higher the surface area, the smaller the pore size of the biochar, and the larger the pore volume, the larger the surface area. There was a strong link between the specific surface area and the micropores and iodine numbers; nevertheless, the biochar iodine numbers were less than their surface areas. The surface area and pore volume of biochar generally grew as the process temperature increased, peaking at 700 °C, and then decreased as the temperature increased even higher [25].

4. Biochar Characterization

The essential characteristics of biochar must be identified, and the numerous applications must be predicted, through physical and chemical characterizations. The properties of each biomass, which include proximate analysis (ash and moisture content), calorific value, fractions of fixed carbon, volatile components, fractions of lignin, cellulose, and hemicellulose, inorganic substances, true density, particle size and moisture content, are considered during the thermal conversion process [26].

Modification of Biochar

Numerous techniques have been employed to modify biochar so that its qualities can be modified for environmental purposes. The most popular techniques are chemical, physical, biological, and nano scale modification [27]. The major types of modification are changes to acidity, alkalinity, oxidising agents, metal salts, and carbonaceous compounds. DigSBiochar was prepared by *Burkholderia* sp. (patent no _TEMP/E-1/56831/2023-DEL & 202311062577). Physical modification mainly includes steam and gas purging. Biochar modification which is shown in **Figure 3**.

The most common and effective method for long-term CO_2 sequestration is biological CO_2 fixation by plants and microbes. The microorganism involved in CO_2 sequestration is a mixture of Bacteria and Archaea [28]. There are six known mechanisms by which microbes can fix CO_2, although the Kelvin–Benson–Basham (CBB) pathway is the most common [29,30]. With the help of the well-known enzymes ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) and carbonic anhydrase 3, the microorganism sequesters CO_2 through a carbon concentrating process [31]. These bacteria are capable of converting CO_2 into biomass and bio products such EPSs, polyhydroxyalkanoates, and lipids, among others [32].

It has been proven that *Serratia* sp. ISTD04 can sequester CO_2 and produce products with value added [31]. So we can dope carbon sequester bacteria with biochar for enhancing soil quality. There are many other applications for biochar, and they are expanding quickly, aside from agriculture, which is probably the most widely recognised. Biochar has a vast range of applications, including construction materials like concrete and asphalt, innovative carbon-based composites, bioplastics, and even medical applications. This is all possible while research and technology continue to evolve, and new use cases are being discovered. Biochar can be produced from vast amounts of bio-waste; it is becoming more and more popular in developing countries as a fertiliser with improved soil characteristics. According to results from ongoing practices, the Modified University of Cape Town procedure is now the least expensive phosphate capture method in the USA, while material precipitation seems to be the most cost-effective method throughout the rest of the developed world. For the first time, using broken cellulose casings which are widely available and becoming more and more abundant worldwide has been recommended. The sorbent was subsequently activated using calcium chloride ($CaCl_2$), which is a waste of money because it will eventually be utilised for agronomic purposes. Pilot scale tests show that this new sorbent can extract 31.8 kg P t^{-1} with 52.5 mg of extractable P L^{-1} from sludge water. The most noteworthy discovery is that the novel sorbent efficiently gathers phosphate, mostly as calcium phosphates (CaP) (191.5 g CaP t^{-1}), which are the most advantageous for plant feeding [33]. Grass cuttings have long been in excess in many cities. Since many modern technologies have large acquisition and variable costs, their management is typically financially difficult. It was determined if it is technically and financially possible to handle mashed cutting of urban green on a commercial scale using the recently introduced concept of anaerobic fermentation followed by continuous pyrolysis. According to an evaluation of the idea, the anaerobically fermented residue can then be pyrolyzed to produce high-quality charcoal in addition to biogas. The suggested remedy has been demonstrated to strengthen the economy as a whole [34].

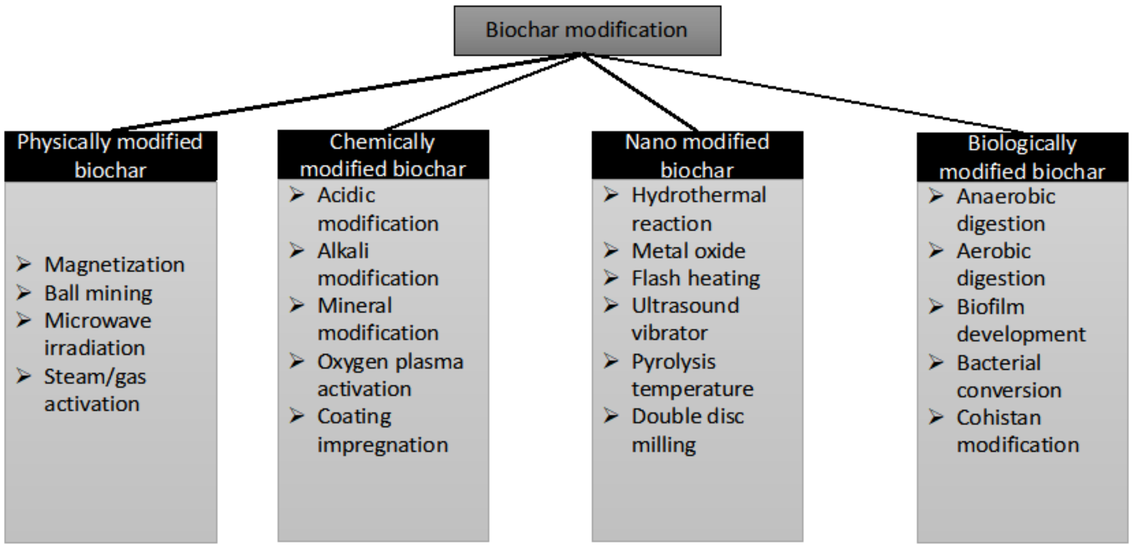

Figure 3. Types of biochar modification.

5. Persistence and Sequestration of Carbon in Soil

5.1. Soil in Regulation of Climate

The largest reservoir of terrestrial carbon (C) stocks is found in soils, and it plays a role in the "climate regulation" of NCP. It is regulated by emissions and sequestration of greenhouse gases (GHGs), biogenic volatile organic compounds, and aerosols, as well as biophysical feedbacks (e.g., albedo, evapotranspiration), affecting soils as sinks and sources of atmospheric carbon dioxide [35]. They are an important part of the global carbon cycle and include both soil organic carbon (SOC) and soil inorganic carbon (SIC) [36].

5.2. Fundamentals of Soil Organic Carbon

An organism's faeces, soil microorganisms including bacteria and fungi, decaying plant and animal tissues, and compounds produced during their breakdown create soil organic matter. Fresh plant remains and humus, a substance that has been extensively decomposed, both comprise soil organic matter. Organic materials with high carbon content make up soil organic matter as shown in **Figure 4**.

For instance, specialized soil fungi called mycorrhizae and the roots of many plants form symbiotic connections [37]. Carbon is lost due to microbial respiration. **Figure 5** illustrates the soil's loss of carbon [38].

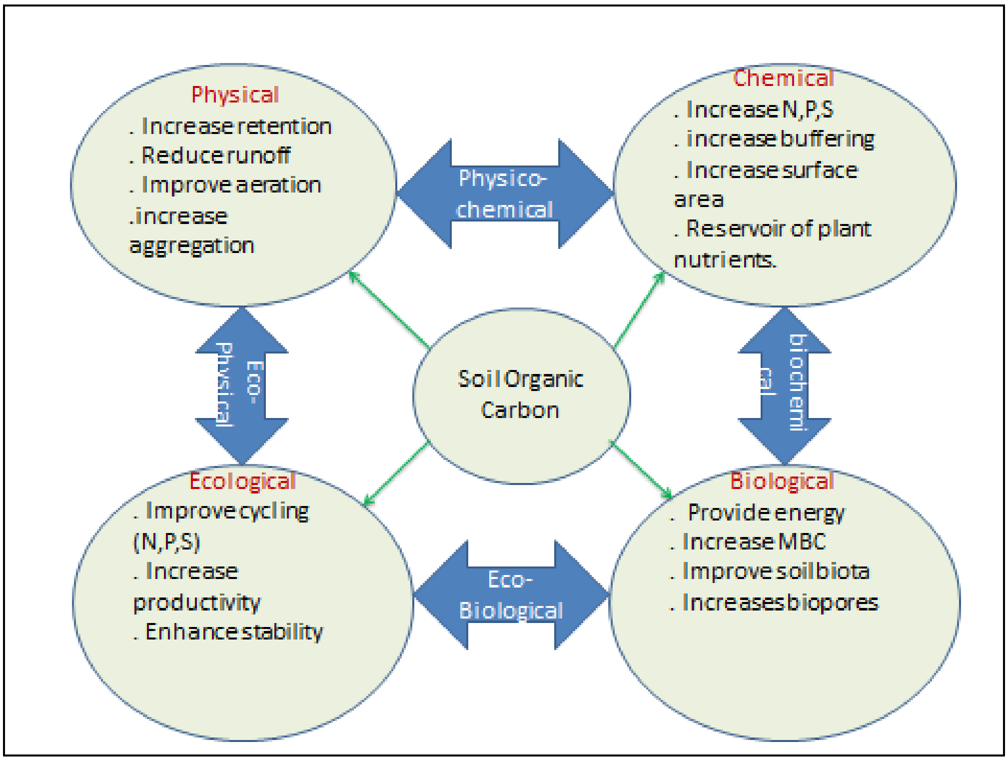

Figure 4. Illustrates the importance of soil organic carbon in strengthening the physical, chemical, ecological, and biological properties of soil.

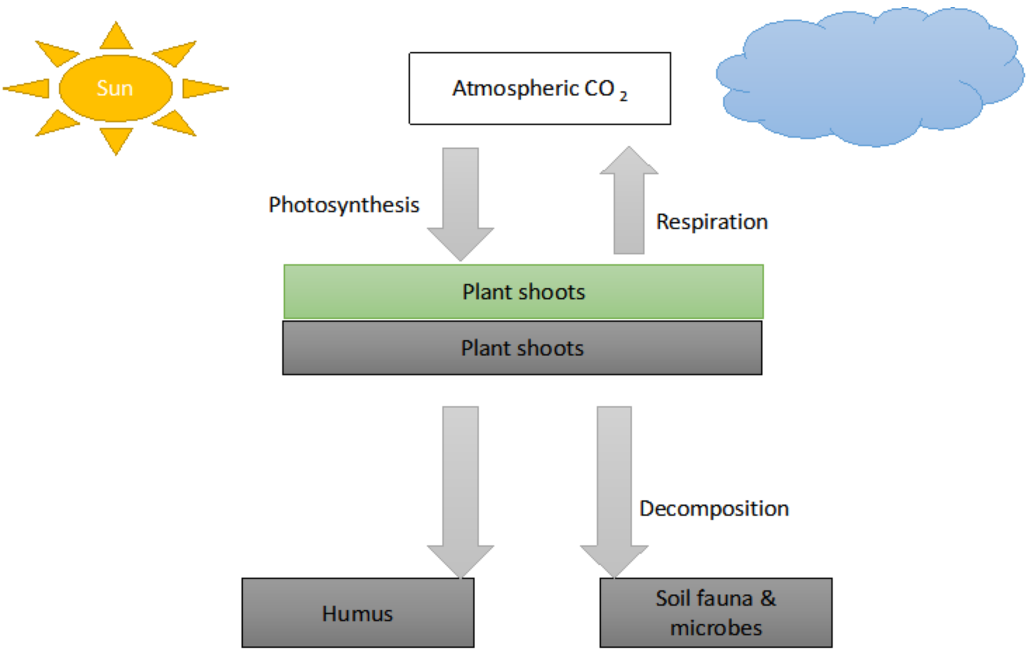

Figure 5. Carbon inputs from photosynthesis and carbon losses from respiration regulate the soil's carbon balance.

5.3. Soil's Carbon and Climate Change

There is mounting evidence that the earth's climate is changing quickly as a result of human activities on going atmospheric emissions of CO_2 and other greenhouse gases (GHGs) [39]. Despite the fact that there are many GHGs (such as N_2O and CH_4), CO_2 has the most effect on global climate change due to its widespread growth from the pre industrial period to the present. Prior to 1850, there were about 280 ppm of CO_2 in the atmosphere. Most recently, there were 381.2 ppm and currently that amount has increased annually by 0.88 ppm (3.5 Gt C/yr) (gigatonnes of carbon per year) [40]. About two thirds of the overall rise in atmospheric CO_2 is attributed to the combustion of fossil fuels, with the remaining one third coming from the loss of soil organic carbon brought on by changes in land use, such as the clearance of forests and the cultivation of land for food production [41].

5.4. Fossil Fuels and Climate Change

Roughly half of the maximum temperature increase caused by burning fossil fuels has already been felt by the planet; nevertheless, effects like rising sea levels and disappearing glaciers won't stop until after 2150. Sustainable agriculture is essential for food security, and sustainable agriculture necessitates innovative management to guide the evolution away from heavily depending on inputs from fossil fuels. Famine and social instability will cause a terrible toll of human suffering if food security is not achieved. Food security at the local, regional, and global levels is expected to be impacted by climate change due to its potential to disrupt food supplies, reduce availability to food, and complicate its utilisation. For American food producers and consumers, it is critical to consider how climate change may impact global food security. Crop residues are a significant and geographically diverse resource that presents a great opportunity for the development of biotechnologies, the management of natural resources, the creation of a circular economy, and the mitigation of climate change. The predicted total crop residue output worldwide was 2.4 Pg C $year^{-1}$ (Petagrams of carbon per year). The projected technical potential for producing biochar, assuming full utilisation of all residues, is around 1 Pg C $year^{-1}$ (3.7 Pg CO_2e $year^{-1}$) (Petagrams of carbon per year). Conversely, the potential limited by current uses and harvest losses is 0.51 Pg C $year^{-1}$ (1.8 Pg CO_2e $year^{-1}$) (Petagrams of carbon per year). This results in significant 100-year carbon storage via biochar in the range of 0.36–0.72 Pg C $year^{-1}$ (1.25–2.64 Pg CO_2e $year^{-1}$) (Petagrams of carbon per year), which is comparable to 3% to 7% of the world's current yearly anthropogenic CO_2 emissions. The carbon dioxide removal impact of sequestered carbon is generally the largest contributor to the overall greenhouse gas impact, according to life-cycle assessments of biochar from crop residue. The carbon dioxide removal potential calculated here offers a strong indication that biochar from crop residue has the technical potential to play a significant role in mitigating climate change [42]. This study looks at how successful internal and external incentives are in increasing the rate at which Chilean farmers who grow annual crops adopt sustainable agricultural practices (SAPs). While extrinsic motivation is embodied in an economic incentive to encourage the implementation of SAPs, we use farmers' attitudes towards sustainable agriculture practices as a surrogate for intrinsic motivation. The Chilean Ministry of Agriculture is in charge of the policy programme we examined, which is known as the System of Incentives for the Agro-Environmental Sustainability of Degraded Soils (SIRSD-S). Adopting (1) limited tillage, (2) enhanced fallow, (3) stubble incorporation, (4) manure use, and (5) compost use were all considered forms of sustainable behaviour. An estimated count model showed that the adoption of sustainable agriculture techniques was significantly predicted by both motivational sources and their interaction. The Agro-Environmental Sustainability of Degraded Soils was a major factor in the adoption of sustainable agricultural practices by farmers who lacked intrinsic motivation, as opposed to intrinsically motivated farmers who adopted more sustainable practices regardless of extrinsic motivation. Ultimately, it was discovered that the adoption of sustainable agriculture techniques was positively influenced by the perception of the risk of soil erosion and the perceived behavioural control over this risk [43].

6. Factors Affecting the Storage of Soil Organic Carbon (Sequestration)

Precipitation and temperature are the main determinants of plant biomass input and subsequent soil organic carbon breakdown for certain soil types in natural ecosystems. When organic carbon inputs and losses are equivalent, the equilibrium soil organic carbon level can be reached. Management strategies also have an influence on soil organic carbon turnover rates and equilibrium levels in agricultural systems. With cereal crops typically absorbing 30–50% of the annual fixed carbon as subterranean dry matter and the remaining 50–70% as above and below ground residues, a considerable portion of the fixed carbon (fixed C) from photosynthesis is lost after harvest. (For example, root biomass). SOC is governed by numerous variables that intimately interact to contribute to system stability in agro ecosystems. These factors include the characteristics of the soil, the temperature and precipitation of the climate, and the land use and management techniques that are described below [44].

6.1. Soil Depth and Soil Type

The SOC level fluctuates depending on the depth and kind of soil. Soil organic carbon content commonly falls as soil profile depth increases. However, depths more than 50 cm can have a high concentration of soil organic carbon. The relationship between soil organic carbon and soil type is influenced by differences in topography, soil mineral composition, climate, and management practises [45].

6.2. Soil Texture

The texture of the soil can influence both the quantity of soil organic carbon retained in the soil and the net mineralization of soil organic matter. Their research revealed that soil organic carbon increased with soil volume and that clay soils saw the least amount of soil organic carbon loss during agriculture. Increasing soil concentration increases the carbon holding capacity of the soil. Additionally, increasing the amount of silt also increases water holding capacity, which creates an interaction between soil texture and climate that regulates ecological processes [46].

6.3. Composition of Soil Minerals

The amount of organic carbon stored in soil, how long it takes for it to turn over, and the fluxes of carbon between the atmosphere and the biosphere all depend on the mineral composition of the soil. Compared to other cation types, the presence of multivalent cations such as Ca^{2+}, Al^{3+} or Fe^{3+} promotes the formation of organic carbon [47].

6.4. Soil pH

The activity of microbial enzymes in the soil (hydrogen ion activity) is controlled by the pH of the soil. Indicating that both hydroxyl and hydrogen ions are inhibitors of microbial respiration, mineralization of soil organic matter proceeded most quickly at a pH optimal of approximately 6.7 [48]. Decreased soil pH causes an increase in SOC in natural ecosystems, provided significant carbon inputs are generated, as soil surfaces become more saturated with organic carbon and the pH decreases, soil microbial activity decreases [48,49].

7. Agricultural Management for Soil Organic Carbon Storage and Sequestration

The net balance of organic carbon inputs and losses is reflected in soil organic carbon. Soil carbon storage can be increased through agricultural management practices that increase carbon input by improving crop yield, applying external sources of carbon (such as animal manure, compost, and Biosolids), or reducing carbon loss [50]. However, encouraging soil carbon sequestration is a difficult and time-consuming task. The two "gold" principles of sustainable management practices) increasing carbon stocks (i.e., C inputs) through continuous and abundant carbon inputs into the soil; and ii) lowering GHG emissions from the soil (i.e., C losses) must be considered to achieve soil sequestration. In addition to research and policy changes, national governments and other agencies should work towards carbon farming together with global initiatives like the Global Soil Partnership and the "4 per 1,000" Initiative, as well as regional public private partnership initiatives on carbon credits for Regenerative Agriculture such as Grow Indigo CIMMYT-ICAR in India. This will be essential for South Asia's soil carbon sequestration programme to be successful in combating climate change [51].

7.1. The Role of Biochar in Carbon Sequestration

Carbon sequestration is the term used for the process by which a plant absorbs CO_2 and stores it in long lasting stores of plant biomass and soil organic carbon [52]. Among the several methods of carbon sequestration in soil, the use of biochar is seen to be the most promising one for the long term storage of carbon contained within biomass. Australia's natural biochar sink is believed to store roughly 21 million t of carbon dioxide each year. According to early calculations, atmospheric CO_2 levels might be returned to levels found before AD 1752 by 2050 if 2.5% of the world's agricultural land generated biochar (ideally from effluents for use in topsoil). If slash and burn agriculture is replaced by slash and char systems, all anthropogenic land use change emissions could be reduced annually by

12% [53]. The major factors contributing to biochar's enormous potential for carbon sequestration are its high carbon content and exceptionally stable form. The general process of carbon sequestration by biochar is presented in **Figure 6.** The following characteristics of biochar can be grouped as the process of increased potential for long term carbon storage by applying biochar to soil. Apart from being a stable and rich form of carbon, biochar also manages agricultural and forestry waste and increases carbon sequestration rates [54,55].

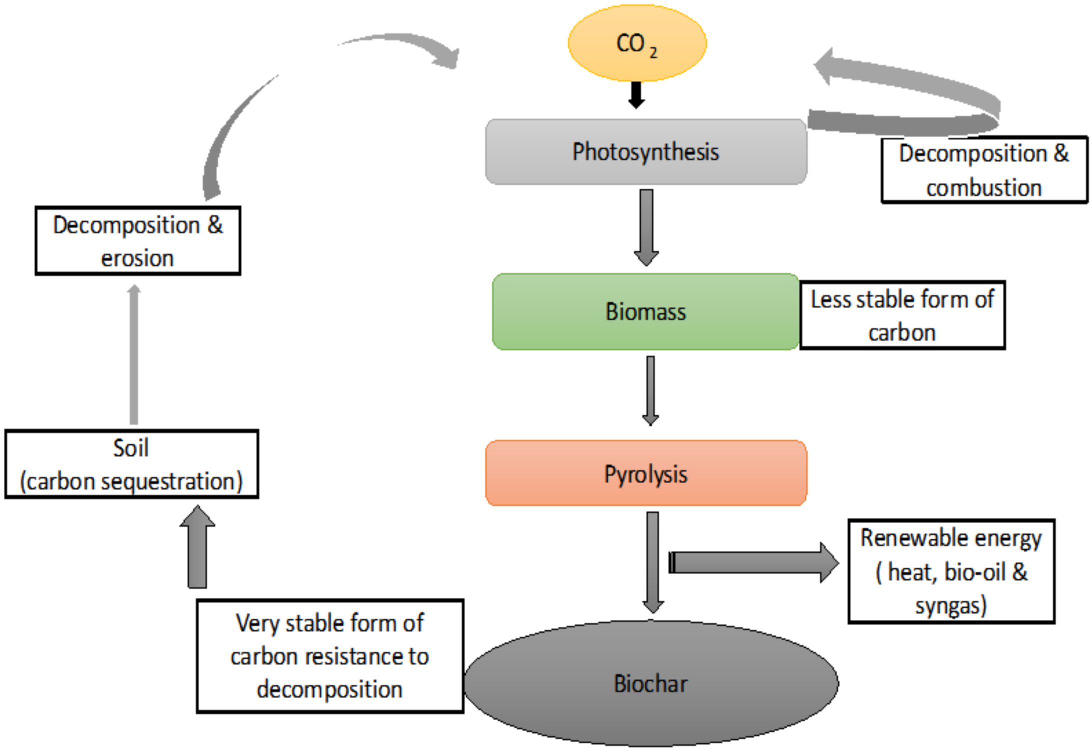

Figure 6. Phenomenon of carbon sequestration by biochar.

7.2. Land Carbon Sequestration and Biochar

The process by which CO_2 is taken out of the atmosphere and stored in the carbon pool of the soil is known as soil carbon sequestration. Biochar, sometimes referred to as biological charcoal, serves as a carbon sink on agricultural land by removing carbon from the atmosphere. It is possible to employ biologically inaccessible biochar to store fixed carbon in soil for a long period of time, allowing it to absorb net carbon from the atmosphere [56]. Additionally, biochar slows water runoff and reduces the demand for fertilizer. The effect of biochar on soil property is shown in **Table 2**. Every year, 30 giga t of carbon are removed from the atmosphere by agriculture, but 30 giga t of carbon are also released back into the atmosphere as plants die, so there is no net change. When biochar is combined with compost, soil, and plants, it recovers and stores a significant amount of carbon in the ground, resulting in a sustained and significant decrease in atmospheric GHG levels [57]. Biochar also reduces the need for fertilizer and increases agricultural productivity in marginal soils. And because biochar acts like a sponge, it drastically reduces runoff, (which helps rivers, streams, and oceans, and reduces the need for petrochemical fertilizers) [58].

Table 2. Quantitative effect of biochar on various soil parameters and its impact on crop productivity.

S. No.	Biochar (Raw Material and Dose)	Parameter	Impact
1	Biochar from green waste applied @ 5t ha^{-1}	Fertilizer use efficiency	10%–30% increased
2	Biochar from plant biomass @ 10 to 120 t ha^{-1}	Biological nitrogen Fixation	Increased at 10 t ha^{-1} and decreased at 120 t ha^{-1}
3	Conifer charcoal and hard wood charcoal @ 0%–45% Volume	Soil moisture retention	18% increase in sandy soils and 11.1% decrease in clayey soils
4	*Acacia mangium* bark biochar @ 10 L m^{-2}	Arbuscular Mycorrhizal fungi	Increased up to 42%

Table 2. *Cont.*

S. No.	Biochar (Raw Material and Dose)	Parameter	Impact
5	Mesquite biochar @ 10%	Porosity	Increased up to 12%–40%
6	Tobacco stalk biochar @ 1 t ha^{-1}	Nutrient leaching	Slow N and K leaching in light textured soils
7	Mangrove biochar application @ 10 t ha^{-1} in rice crop	Methane emission	21.1% decreased in first season and 24.9% decreased in the second season
8	Biochar (Meta-analysis)	Cation Exchange capacity	Increased by 45%
9	Municipal bio-waste biochar @ 10 wt%	Emission of nitrous oxides	Reduced by 89%
10	Biochar from cacao shell, oil palm @ 30 t ha^{-1}	Liming effect	pH of soil of Cacao shell biochar increases by 0.5 units, 0.05 units increase of oil palm shell biochar and 0.04 units increase of rice husk biochar.
11	Biochar from Eucalyptus wood, bamboo, and rice husk @ 5–20 t ha^{-1}	Alimunium toxicity	Decreased soluble Alimunium

7.3. Biochar and Climate Change

Biomass typically has a carbon content of 45–60% and an oxygen content of 35–40%. Hydrogen, nitrogen, and tiny amounts of minerals make up the remaining elements. A considerable amount of carbon dioxide is emitted into the atmosphere when biomass deteriorates or is burned, which contributes to the adverse effects on the climate and may be prevented by making biochar instead [39]. In a reference system devoid of biochar, plants absorb CO_2 from the atmosphere through photosynthesis, and when they break down fixed carbon in the soil, they release it back into the environment. Nitrous oxide, a potent GHG, is another form of reactive nitrogen that escapes from soil and enters the atmosphere [59]. Finally, the generation of bio energy in conjunction with fossil fuels during the pyrolysis process can eliminate the need for those fossil fuels (seen on the picture as a net reduction in atmospheric CO_2) [60]. A potent tool for addressing the climate emergency is biochar. This enables a decrease in global fossil fuel usage and may be a sustainable method of lowering greenhouse gas emissions in industrialized nations. Crop yields rise because of the usage of biochar enhances the physical, chemical, and biological qualities of the soil. **Table 3** provides the quantitative impact of biochar on crop output. Biochar application improved the seed germination, root density and crop yield [36]. The high porosity of biochar may improve the overall physicochemical and biological characteristics of supplemental soils. The enormous porous surface area of biochar may serve as an indirect barrier to microbe survival, while the organic compounds it has absorbed may promote the growth of bacteria and fungi [61]. The Intergovernmental Panel on Climate Change (IPCC) clearly said in its August 2021 report that deforestation is directly responsible for the decade-long increase in CO_2 levels in the atmosphere, a surge that is unmatched in the previous two million years. As carbon sinks, forests remove harmful carbon from the atmosphere and use photosynthesis to convert it to biomass. Reforestation can address other environmental problems including soil erosion and barren land while also mitigating the effects of climate change. A global effort will be needed to establish enough tree cover to have a significant impact on rising temperatures. Promising projects have been initiated by governments, business organisations, and local communities worldwide. For instance, 1t.org wants to plant one trillion trees with the help of communities all around the world. This would reduce global emissions by about 33%, which is what is needed to reach the targets set forth in the Paris Agreement. This organisation uses crowdsourcing, scaling plans, and multi-stakeholder dialogues to encourage, mobilise, and enable companies to fulfil afforestation commitments.

Table 3. Quantitative effect of biochar on crop yield, productivity and effects.

S No	Crop	Biochar Source and Dose	Soil Properties	Effect
1	Wheat & Corn	5–20 t ha^{-1}	Sandy loam	Yield of wheat and corn will increase
2	Radish	0–2.5 t ha^{-1}	Loamy sand	Boost the production of dry matter
3	Soyabean	Oak tree, 10 t ha^{-1}	Loam	Valuable dry matter production increase
4	Onion	Softwood, 29 & 58 t ha^{-1}	Sandy Loam	Effect of biochar on crop is neutral
5	Cucumber	Litchi branch, 10–30 t ha^{-1}	Acidic red soil	Positive effect on crop yield
6	Tomato	Conocarpus, 0%–8% w/w	Sandy soil	14%–43.3% yield increase
7	Cherry tomato	Wastewater sludge, 10 t ha^{-1}	Chromosol	64% increase in yield due to use of biochar while, in combination of biochar and fertilizers, yield increased by 97% as compared biochar alone.
8	Rice	Wood residues, 0–16 t ha^{-1}	-	Use of biochar without N fertilizers reduced in yield of soils.
9	Durum wheat	Coppiced woodlands, 30 & 60 t ha^{-1}	Silty Loam	Yield increase upto 30%
10	Mung bean	0–100 t ha^{-1}	-	Higher grain yield of 4.2 g/pot obtained at 25 t ha^{-1}

8. Emerging Technologies for Measuring Soil Organic Carbon in Agricultural Lands

Knowing the magnitude of the carbon pool and its ability for utilization as a carbon sink is therefore of utmost relevance given the rising concern about the effects of agriculture on the environment and the need to look for ways to decrease these impacts through carbon sequestration. Agricultural soils need to sequester more carbon; hence there is a need for accurate monitoring and measurement techniques [62]. The problem, however, is that monitoring soil organic carbon stock and monitoring carbon transfer are difficult tasks. Artificial intelligence has received a lot of attention recently as one of the key tools for efficient and successful data analysis. The number of publications and citations related to the use of Artificial Intelligence and machine learning in the context of agriculture and soil carbon measurement has increased [63]. A comparison of the number of articles and citations related to Artificial Intelligence and ML in agro technology between 2010 and 2021 is shown in **Table 4**. Farmers have the chance to manage fields and evaluate soil health more effectively and with fewer resources through the use of data driven software powered by Artificial Intelligence. This is especially important when working to promote carbon sequestration on agricultural lands as understanding the changes taking place within an ecosystem depends on having a source of reliable and accurate data [64].

Table 4. A comparison of the number of articles and citations related to AI and ML in agro technology between 2010 and 2021.

Keyword Search	Publication		Citation	
	2010	**2020**	**2010**	**2020**
Machine learning and Remote sensing	5,866	47,550	73,257	692,907
Artificial Intelligence and Agriculture	4,405	33,405	54,666	316,358
Machine learning and SOC	9,693	79,800	211,518	1,493,427
Machine learning and Hyper spectral imaging	564	7,957	6,851	131,008

8.1. Remote and Proximal Soil Sensing

A greater understanding of soils is required at ever higher resolutions. As an alternative to analytical observations, full geographical data regarding soil parameters like soil organic carbon may be collected using remote sensing (RS) and proximal soil sensing (PSS). Hyperspectral data from images has been found to be an efficient data source for monitoring, describing, and mapping soil organic carbon geographical variability. Sensors tend to be put on various carrying platforms for efficient in field measurements. Each sensor that connects with a specific system uses hyperspectral imagery to collect information [63]. Hyperspectral imaging is said to be more accurate than multispectral imagery. Hyper spectral sensors can concurrently collect thousands of considerably smaller bands (10–20 nm), making them more sensitive to minute changes in reflected energy. In contrast to multispectral photography, which captures electromagnetic radiation using just 3 to 10 larger wavebands, multispectral sensors may simultaneously collect thousands of smaller bands. But both multispectral and hyperspectral sensor photography have their own limitations, thus determining the best platform depends upon the requirements of the work [65]. **Table 5** below provides a summary of the advantages and drawbacks of multispectral and hyper spectral pictures based on the appropriate sensor platform. Other difficulties with using optical images for estimating soil carbon concentration, as well as methods for solving those using different AI algorithms, have been explored and will be discussed in more detail in below [66].

Table 5. Each sensor platform's benefits and drawbacks for multispectral and hyperspectral imaging.

Imagery	Platform	Advantages	Disadvantages
Multi-spectral	Satellite	• Short revisit time • Higher data archive • Accessing of remote areas • Auxiliary data provision • Readily available	• Requirements for geometric, atmospheric correction • Impact by sun illumination • Affected by cloud coverage • Low signal ratio due to a short • Integration time
Hyper-spectral	Proximal	• High accuracy • Cost effective	• Low temporal resolution • Not suitable for large area
	Airborne	• High spatial resolution • Give information for impassable areas	• Limited flight timing • Legal constrict for the flights • Technically demanding processing of information • High operational complexity

8.2. Modern Applications of Artificial Intelligence

Precision agriculture could benefit from machine learning. Precision farming involves tracking and detecting crops that require maintenance. These methods include weed and disease detection, soil, and plant health monitoring, over irrigation prevention, and water conservation. and can get information about how to grow and harvest crops. In agroforestry, ML tracks the health of forests and peat lands and forecasts the probability of fire. **Figure 7** below indicates the wide range of AI uses in modern agro technology which promotes the growth of the field as a whole [67].

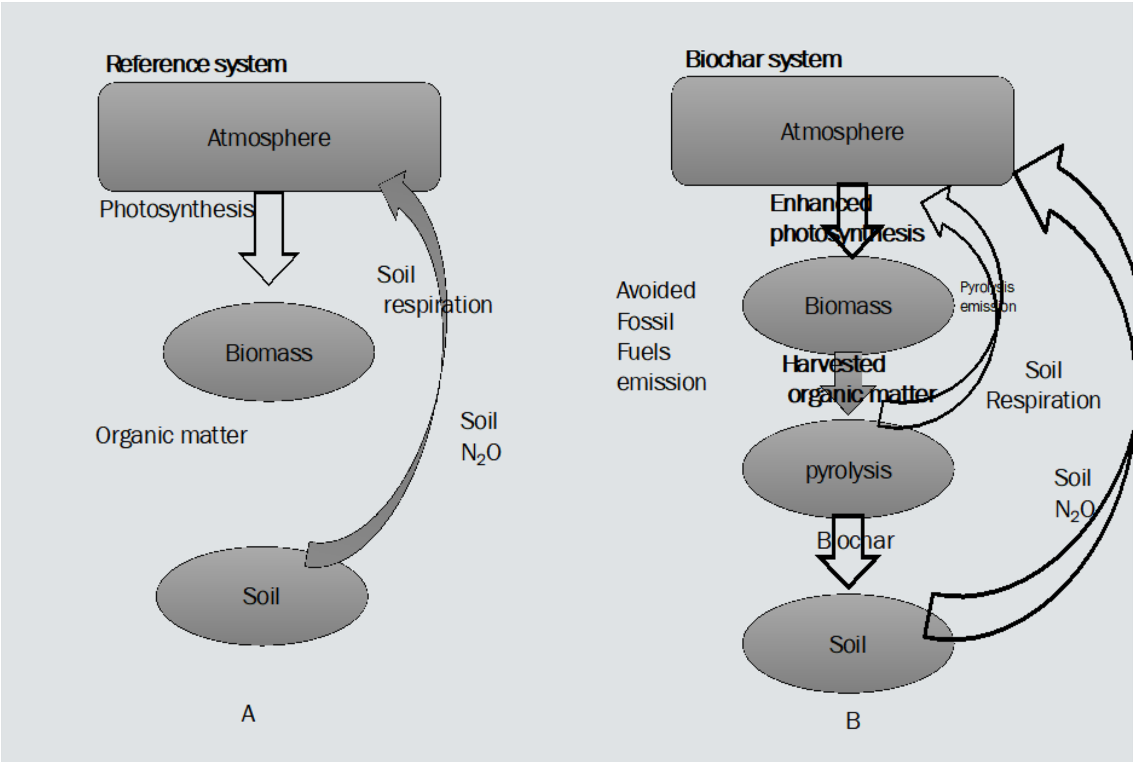

Figure 7. Main impact of biochar on greenhouse gas fluxes and carbon capture and utilization.

8.3. Artificial Intelligence for Soil Carbon Estimations and Monitoring

Agriculture 5.0 is a concept in which data driven agriculture combined with integrated robotics and artificial intelligence helps in the use of technology requiring precision farming practices and unmanned operations and autonomous decision support systems. Five main steps are involved in crop management and smart choices on farms that follow the agriculture 5.0 philosophy shown in **Figure 8**. With the use of nearby and remote sensors, the data of area is initially generated from the crop and soil [68]. A promising method to measure soil organic carbon concentration and estimate soil organic carbon stock with better accuracy and lower costs is the integration of remote sensing and machine learning. To meet the demand for precise soil organic carbon measuring methods as we move towards sustainable agriculture practices, this trio of cutting-edge technology provides quick, easy, and affordable solutions. In addition to improving our knowledge of the dynamics of soil organic carbon, this integration encourages sustainable land management techniques that support agricultural productivity and environmental care [69].

A variety of monitoring functions, such as crop health analytics and current and predicted weather, can be carried out by different kinds of satellites. Drones versus satellites, when flying low, can identify pest species and crop disease symptoms. Drones and satellites both cover large areas and are independent of wind and rain. For this reason, space-retrieved imagery may be less expensive when great precision is not required. Every technique has benefits and drawbacks when used. Therefore, wherever possible, combining drones with satellite imagery is the best and most economical course of action. The development of artificial intelligence and machine learning soil carbon modelling may either excite and enthral us with the beauty of machine-generated soil carbon data, maps, and models that we believe will have a significant impact on carbon science and how it is applied in carbon policies, carbon crediting, and carbon management, or it may make us feel confused, helpless, and meaningless because only the machine knows. The hazards include human manipulation (i.e., how the model is tweaked and fitted) and misuse of AI-generated soil carbon hyper reality are possible [70]. Artificial Intelligence is a family of technologies rather than one. Increased output and productivity in sectors like agriculture, food production, and other logistics could result from using AI to support efforts to end hunger. One example is Farm View, which combines robots, AI, and sensor technologies to enhance crop management and plant breeding. It was created by Carnegie Mellon University AI researchers. In developing nations where there is the most need, this research focuses on crop varieties like sorghum, an African grain that can withstand heat. AI can also be used to create more accurate indicators of the distribution of poverty, its rate of spread, and the best places to deploy resources. For example, a research team located in the US is estimating consumption spending and asset richness in African countries by superimposing high-resolution daylight photographs over night-time images and applying machine learning algorithms [71].

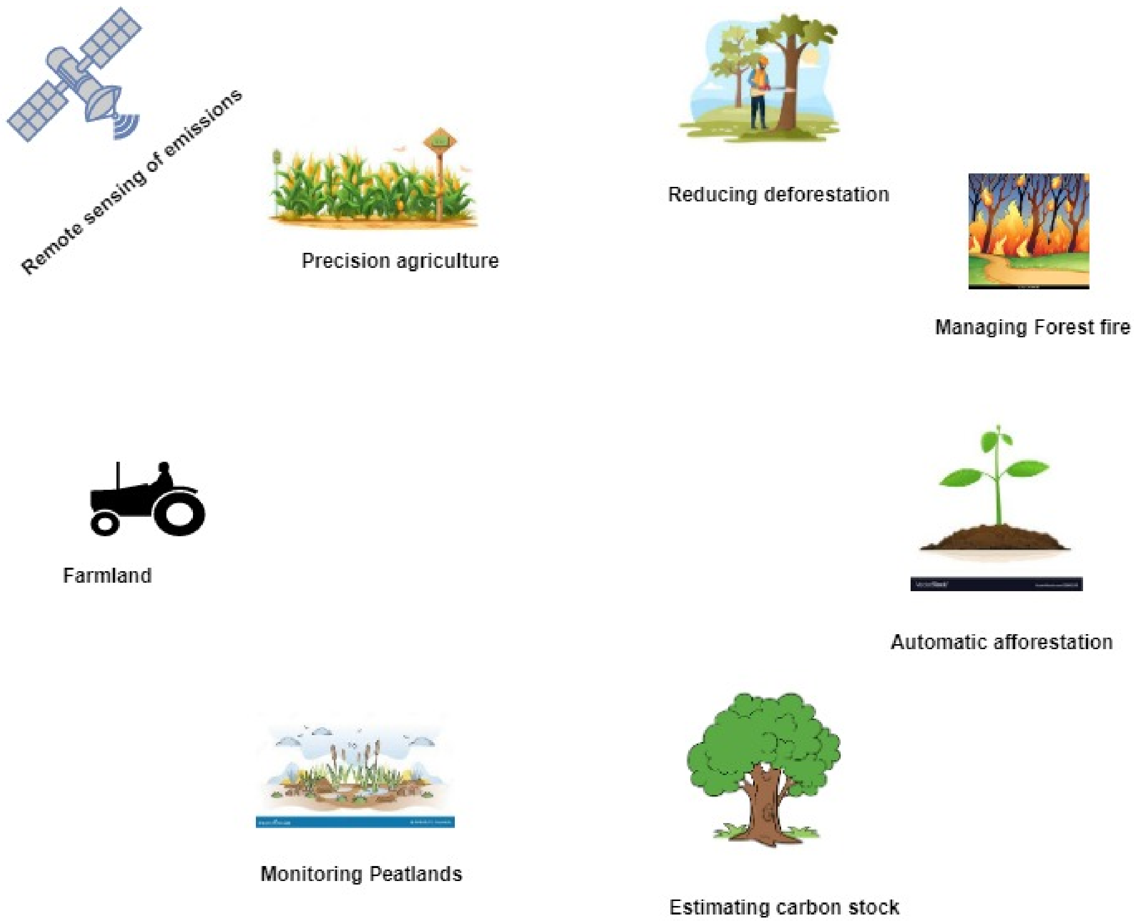

Figure 8. Shows how AI is being used in numerous agro technology sectors.

8.4. Post Measurement Data Processing and Prediction

According to past research, a few soil examinations have already incorporated AI and statistical approaches with effectiveness. Decision trees and artificial neural networks are illustrations of supervised learning techniques that employ past data to establish links between contributing elements. Once these methods are trained, they can be used with new, pre-screened input data to generate estimates of organic carbon concentration [23]. It has proven challenging to determine the amount and regional distribution of soil organic carbon. To establish if soil carbon sequestration may have a measurable influence on climate change mitigation, such information is required [72].

Therefore, the research created an ML based data driven statistical model that utilises an extensive dataset of spatially specific environmental variables and a worldwide compilation of soil organic carbon profile observations to determine the overall effect of changes in land use on soil organic carbon at globally [73]. The model identified important locally based techniques of soil organic carbon loss that corresponded to some of the major agricultural producing fields and demonstrated a serious loss of soil organic carbon during the preceding 200 years [74].

According to the results, the main variables for topsoil SOM predictions in the study's predictive models included climatic and topographical conditions, remote sensing reflectance, and vegetation indices

9. Steps towards Smart Agriculture

Biochar is an organic material that has been burned. Biochar is described by the International Biochar Initiative as "a solid material obtained from the thermochemical transformation of biomass under oxygen limited conditions." Biochar is produced by gasifying, pyrolyzing or dry carbonizing biomass in both solid and liquid forms. Biomass is created through hydrothermal carbonization under pressure. In this procedure, the feedstock is broken down by a number of concurrent liquid phase processes, such as hydrolysis, dehydration, decarboxylation, aromatization and condensation, which reduces the feed's oxygen and hydrogen contents [75]. Despite all the advantages that biochar may offer, adding it to agricultural soils is controversial. The yield of the major crops must be improved to fulfil the rising food demand. Additionally, some modification was carried out on biochar using feedstock sewage sludge & agricultural waste. Despite the fact that the biomass feedstock used to produce biochar and DigSBiochar both contain cellulose, hemicellulose, and lignin and the char solid products' physical and chemical properties are noticeably different [76]. For example, DigSBiochar has H:C and O:C ratios that are higher than biochar and nearly natural coal. The different reaction mechanisms, production methods and operational environments are to blame for these variations in the physicochemical characteristics of the chars. The possible applications of chars in many domains, such as adsorbent materials, vary depending on their distinct features [77]. DigSBiochar, for instance, has a high capacity for pollutant adsorption because it contains acidic functional groups available on its surface. DigSBiochar's porous structure may be improved by raising temperature and residence time, which expands the material's potential for usage as an adsorbent. The utilization of *Burkholderia* sp. ISTR5, gasification, HTC, pyrolysis and the addition of calcite based nano bio composite had a substantial impact on the parameters of the biochar, including yield, fixed carbon and oxygen content, and pore size distribution [5]. The in situ loading of metal nanoparticles on DigSBiochar materials reveals advantages by minimizing the duplicated reactions and impurities by using alternate decreasing agents [78]. Human nourishment comes exclusively from agriculture. Since fossil fuels power the majority of farm equipment, they accelerate climate change by adding to greenhouse gas emissions. By encouraging the use of renewable energy sources including solar, wind, biomass, tidal, geothermal, small-scale hydro, biofuels, and wave-generated power, such environmental harm can be lessened. For the agricultural sector, these renewable resources hold enormous promise. Subsidies should be offered to farmers to stimulate the usage of technology related to renewable energy. Human nourishment comes exclusively from agriculture. Since fossil fuels power the majority of farm equipment, they accelerate climate change by adding to greenhouse gas emissions. By encouraging the use of renewable energy sources including solar, wind, biomass, tidal, geothermal, small-scale hydro, biofuels, and wave-generated power, such environmental harm can be lessened. For the agricultural sector, these renewable resources hold enormous promise. Subsidies should be offered to farmers to stimulate the usage of technology related to renewable energy. using natural resources more than the environment can sustainably offer is the objective of sustainable development. It is important to take into account every aspect of sustainability, especially as it relates to increasing soil carbon sequestration. The Sustainable Development Goals (SDGs) of the United Nations were established in 2015 with sustainability as their central subject. The 17 Sustainable Development Goals (SDGs) represent an urgent appeal for all nations to join forces in an international partnership to address climate change, combat inequalities, stimulate economic growth, and improve health and education. Because of this, we shall attempt to establish, within the framework of sustainable development, a world with no land degradation." SDG 15.3 on land degradation neutrality (LDN) was adopted by the UN General Assembly in September 2015. The goal is to "by 2030, combat desertification, and restore degraded land and soil, including land affected by drought and floods, and strive to achieve a land-degradation neutral world."

10. Future Approaches

Biochar, carbon rich, stable by products of the thermal cracking of biomasses in an oxygen free environment, is produced. A current problem that requires updated study is the hasty development of engineered biochar synthesis through various technologies and their use in the fields of energy and environment [79]. The main issues affecting society and economic activity and posing a serious danger to the environmental sustainability are the growing concentration of hazardous waste and the need for more energy globally [80]. In order to reduce environmental contaminants, direct interspecies electron transfer (DIET) in anaerobic digestion (AD) can be accelerated by adding biochar as a supplement, as a way to increase the process's buffering capacity, and as a catalyst and/or catalytic support in bio refineries [81,82]. Due to its superior adsorption ability, biochar's exposed pores effectively reduce the release of methane (CH_4) while the composting process developed [83]. Engineered biochar has a high porosity, which makes it a superior greenhouse gas (GHG) sink [84]. Use of biochar for specific purposes, such as soil conditioning and fertilization, promoting plant growth, removing pollutants, reducing GHG emissions, storing carbon, and as a catalyst or catalyst in bio refineries and ADs of environmental wastes. Acting as a support has been the theme among many recent reviews [85]. Therefore, reusing and recycling environmental trash to create greener goods and expanding its usage in sustainable bio refineries and environmental management might result in a win situation [86]. Agro industrial effluents (AIE) from bio refineries have high chemical oxygen demand and dye concentrations released into the environment [87]. Treatment of these effluents is an environmental problem because of the sizeable quantity of contaminants they contain, the volume they create, and seasonal changes. The effluent thus poses a major hazard to the environment when released without getting adequate treatment [88]. Biochar is the perfect support material for bio sorbent because of its distinct physical and chemical characteristics. Therefore, developing hybrid bio sorbent from agro waste and effluent materials may make it feasible to fulfil environmental sustainability goals through the redirection of agro waste to establish circular economies [89]. An efficient method to fabricate calcite based Nano bio composite materials by DigSBiochar with help of *Burkholderia* sp. ISTR5 for a self-sustainable system for transferring waste into wealth (Patent no: TEMP/E-1/56831/2023-DEL). A novel composition of biochar biosorbent, named DigLBiochar, generated from agricultural waste (patent no: 202311062577) is reported. By using all methods, we can reuse our waste and enhance crop production and goes towards climate smart agriculture and for various type of environmental application. The research has found the plentiful availability of renewable energy sources in agriculture through an exploration of different sources, including solar, biomass, wind and geothermal energy. Reducing greenhouse gas emissions, increasing energy efficiency and advancing sustainability in food production are all potential benefits of switching to alternative energy sources for energy management in agriculture. We can contribute to a more resilient and sustainable agriculture sector that ensures food security, mitigates climate change and fosters overall sustainable development by advancing energy management methods and encouraging the use of renewable energy in agriculture. Numerous advantages of using renewable energy in agriculture were covered throughout the review. Reduced reliance on fossil fuels, financial savings from better energy efficiency, heightened energy security, and improved environmental sustainability are a few of these. Furthermore, the resilience and self-sufficiency of rural communities can be enhanced by the integration of renewable energy systems into agriculture, particularly in developing nations with inadequate energy infrastructure. Combining renewable energy with current agricultural practices especially manual ones needs more capacity building (to maintain drip irrigation systems, for example), as well as marketing and access to markets for new products and higher yields for already produced goods [90].

11. Conclusions

To address climate change and ensure the well-being of environment, including human populations, current traditional soil management practices need to adapt. The European Union's objective of having 75% more healthy soils by 2030 can be achieved by implementing soil regenerative methods, which have several potential advantages, including soil organic carbon sequestration. Biochar has the potential to be an effective method for sequestering carbon in soil. Its capacity to strengthen carbon storage, ameliorate greenhouse gas emissions, and improve soil characteristics is obvious. Long-term carbon sequestration appears possible due to the stability and persistence of carbon in soils treated with biochar, albeit this depends on several conditions. Context-specific assessments are necessary due to the complex relationships between biochar and soil processes, which are influenced by soil type, climate conditions, and unique features of biochar. Biochar has the potential to significantly contribute to carbon sequestration and the role of emerging technologies in measuring and modelling soil organic carbon in agricultural areas, provided that policies are implemented appropriately, and knowledge is disseminated, and capacities are built. In that context, a wide range of studies has been carried out and highlighted the use of artificial intelligence and machine learning as a key enabler for soil properties applications due to their low cost and spatial coverage. Regenerative agriculture can help transform the industry from one of the main sources of anthropogenic greenhouse gas emissions to one that provides ecosystem and health benefits to all of nature, including humans, by implementing these practices and meticulously recording the results for biodiversity, soil, and other objectives.

Author Contributions

Writing—original draft, conceptualization, investigation, A.K.; investigation, writing, data curation, corrected the Ms properly, K.K.; carried out initial planning, conceptualization, supervision, visualization, writing, editing, and reviewing, I.S.T. All authors have read and agreed to the published version of the manuscript.

Funding

There is no funding available for the review article/research work related to design of the study and collection, analysis and interpretation of data including writing the Ms.

Institutional Review Board Statement

Not applicable. This study did not involve humans or animals, and therefore ethical approval was not required.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data and materials presented in the manuscript or additional supporting files and formats have not been taken from publicly available repositories. All the authors agreed to provide data and materials after request.

Acknowledgments

The authors are grateful to Prof. P.B.Sharma, Vice Chancellor, Amity University Haryana, Gurugram, for necessary help and support related to completion of the research work.

Conflicts of Interest

The authors declare that they have no known competing financial or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AI Use Statement

Grammarly and QuillBot were used solely for language editing, grammar correction, and improvement of clarity. No AI tools were used for data generation, analysis, interpretation, or figure preparation. The authors take full responsibility for the accuracy and originality of the final manuscript.

References

1. Armah, E.K.; Chetty, M.; Adedeji, J.A.; et al. Biochar: Production, application and the future. In *Biochar-Productive Technologies, Properties and Application*; IntechOpen: London, UK, 2022. [CrossRef]
2. Zhang, P.; Min, L.; Tang, J.; et al. Sorption and degradation of imidacloprid and clothianidin in Chinese paddy soil and red soil amended with biochars. *Biochar* **2020**, *2*, 329–341. [CrossRef]
3. Woolf, D.; Lehmann, J.; Ogle, S.; et al. Greenhouse gas inventory model for biochar additions to soil. *Environ. Sci. Technol.* **2021**, *55*, 14795–14805. [CrossRef]
4. Li, S.; Tasnady, D. Biochar for soil carbon sequestration: Current knowledge, mechanisms, and future perspectives. *C* **2023**, *9*, 67. [CrossRef]

5. Ghai, M.K.; Khatri, A.; Thakur, I.S. Utilization of *Burkholderia* sp. ISTR5 for enhanced saccharification and fermentation of agricultural waste for production and upgradation of biogas by calcite-based bio-composite materials. *Bioresour. Technol. Rep.* **2023**, *24*, 101608. [CrossRef]
6. Alkharabsheh, H.M.; Seleiman, M.F.; Battaglia, M.L.; et al. Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: A review. *Agronomy* **2021**, *11*, 993. [CrossRef]
7. Delgado, F.; Gutierrez, V.S.; Dennehy, M.; et al. Stable and efficient metal-biochar supported catalyst: Degradation of model pollutants through sulfate radical-based advanced oxidation processes. *Biochar* **2020**, *2*, 319–328. [CrossRef]
8. Liu, Z.; Wu, X.; Liu, W.; et al. Greater microbial carbon use efficiency and carbon sequestration in soils: Amendment of biochar versus crop straws. *GCB Bioenergy* **2020**, *12*, 1092–1103. [CrossRef]
9. Majumder, S.; Neogi, S.; Dutta, T.; et al. The impact of biochar on soil carbon sequestration: Meta-analytical approach to evaluating environmental and economic advantages. *J. Environ. Manag.* **2019**, *250*, 109466. [CrossRef]
10. Li, M.; Xiong, Y.; Cai, L. Effects of biochar on the soil carbon cycle in agroecosystems: An promising way to increase the carbon pool in dryland. *IOP Conf. Ser.: Earth Environ. Sci.* **2021**, *693*, 012082. [CrossRef]
11. Lal, R.; Monger, C.; Nave, L.; et al. The role of soil in regulation of climate. *Philos. Trans. R. Soc. B* **2021**, *376*, 20210084. [CrossRef]
12. Sakhiya, A.K.; Anand, A.; Kaushal, P. Production, activation, and applications of biochar in recent times. *Biochar* **2020**, *2*, 253–285. [CrossRef]
13. Pradhan, S.; Abdelaal, A.H.; Mroue, K.; et al. Biochar from vegetable wastes: Agro-environmental characterization. *Biochar* **2020**, *2*, 439–453. [CrossRef]
14. Owsianiak, M.; Lindhjem, H.; Cornelissen, G.; et al. Environmental and economic impacts of biochar production and agricultural use in six developing and middle-income countries. *Sci. Total Environ.* **2021**, *755*, 142455. [CrossRef]
15. Ippolito, J.A.; Cui, L.; Kammann, C.; et al. Feedstock choice, pyrolysis temperature and type influence biochar characteristics: A comprehensive meta-data analysis review. *Biochar* **2020**, *2*, 421–438. [CrossRef]
16. He, M.; Xu, Z.; Hou, D.; et al. Waste-derived biochar for water pollution control and sustainable development. *Nat. Rev. Earth Environ.* **2022**, *3*, 444–460. [CrossRef]
17. Palansooriya, K.N.; Wong, J.T.F.; Hashimoto, Y.; et al. Response of microbial communities to biochar-amended soils: A critical review. *Biochar* **2019**, *1*, 3–22. [CrossRef]
18. Pathy, A.; Ray, J.; Paramasivan, B. Biochar amendments and its impact on soil biota for sustainable agriculture. *Biochar* **2020**, *2*, 287–305. [CrossRef]
19. Ghodake, G.S.; Shinde, S.K.; Kadam, A.A.; et al. Review on biomass feedstocks, pyrolysis mechanism and physicochemical properties of biochar: State-of-the-art framework to speed up vision of circular bioeconomy. *J. Clean. Prod.* **2021**, *297*, 126645. [CrossRef]
20. Abdy, C.; Zhang, Y.; Wang, J.; et al. Pyrolysis of polyolefin plastic waste and potential applications in asphalt road construction: A technical review. *Resour. Conserv. Recycl.* **2022**, *180*, 106213. [CrossRef]
21. Thomas, E.; Borchard, N.; Sarmiento, C.; et al. Key factors determining biochar sorption capacity for metal contaminants: A literature synthesis. *Biochar* **2020**, *2*, 151–163. [CrossRef]
22. Maroušek, J.; Trakal, L. Techno-economic analysis reveals the untapped potential of wood biochar. *Chemosphere* **2022**, *291*, 133000. [CrossRef]
23. Awan, S.; Ippolito, J.A.; Ullman, J.L.; et al. Biochars reduce irrigation water sodium adsorption ratio. *Biochar* **2021**, *3*, 77–87. [CrossRef]
24. Hien, T.T.T.; Tsubota, T.; Taniguchi, T.; et al. Correction to: Enhancing soil water holding capacity and provision of a potassium source via optimization of the pyrolysis of bamboo biochar. *Biochar* **2021**, *3*, 63–63. [CrossRef]
25. Phuong, D.; Miyanishi, T.; Okayama, Y.; et al. Pore characteristics and adsorption capacities of biochars derived from rice residues as affected by variety and pyrolysis temperature. *Am. J. Innov. Res. Appl. Sci.* **2016**, *2*, 179–189.
26. Singh, H.; Northup, B.K.; Rice, C.W.; et al. Biochar applications influence soil physical and chemical properties, microbial diversity and crop productivity: A meta-analysis. *Biochar* **2022**, *4*, 8. [CrossRef]
27. Praveen, S.; Jegan, J.; Bhagavathi Pushpa, T.; et al. Biochar for removal of dyes in contaminated water: An overview. *Biochar* **2022**, *4*, 10. [CrossRef]
28. Thakur, I.S.; Kumar, M.; Varjani, S.J.; et al. Sequestration and utilization of carbon dioxide by chemical and biological methods for biofuels and biomaterials by chemoautotrophs: Opportunities and challenges. *Bioresour. Technol.* **2018**, *256*, 478–490. [CrossRef]

29. Maheshwari, N.; Krishna, P.K.; Thakur, I.S.; et al. Biological fixation of carbon dioxide and biofuel production using microalgae isolated from sewage waste water. *Environ. Sci. Pollut. Res.* **2019**, *22*, 27319–27329. [CrossRef]
30. Kumar, M.; Sundram, S.; Gnansounou, E.; et al. Carbon dioxide capture, storage and production of biofuel and biomaterials by bacteria: A review. *Bioresour. Technol.* **2018**, *247*, 1059–1068. [CrossRef]
31. Kumar, M.; Kumar, M.; Pandey, A.; et al. Genomic analysis of carbon dioxide sequestering bacterium for exopolysaccharides production. *Sci. Rep.* **2019**, *9*, 4270. [CrossRef]
32. Kumar, A.; Saini, K.; Bhaskar, T. Hydochar and biochar: Production, physicochemical properties and techno-economic analysis. *Bioresour. Technol.* **2020**, *310*, 123442. [CrossRef]
33. Stávková, J.; Maroušek, J. Novel sorbent shows promising financial results on P recovery from sludge water. *Chemosphere* **2021**, *276*, 130097. [CrossRef]
34. Maroušek, J.; Zeman, R.; Vaníčková, R.; et al. New concept of urban green management. *Clean Technol. Environ. Policy* **2014**, *16*, 1835–1838. [CrossRef]
35. Ghosh, P.; Shah, G.; Chandra, R.; et al. Assessment of methane emissions and energy recovery potential from the municipal solid waste landfills of Delhi, India. *Bioresour. Technol.* **2019**, *272*, 611–615. [CrossRef]
36. Lorenz, K.; Lal, R. Biochar application to soil for climate change mitigation by soil organic carbon sequestration. *J. Plant Nutr. Soil Sci.* **2014**, *177*, 651–670. [CrossRef]
37. McHenry, M.P. Agricultural bio-char production, renewable energy generation and farm carbon sequestration in Western Australia: Certainty, uncertainty and risk. *Agric. Ecosyst. Environ.* **2009**, *129*, 1–7. [CrossRef]
38. Kundu, S.; Bhattacharyya, R.; Prakash, V.; et al. Carbon sequestration and relationship between carbon addition and storage under rainfed soybean–wheat rotation in a sandy loam soil of the Indian Himalayas. *Soil Tillage Res.* **2007**, *92*, 87–95. [CrossRef]
39. Lehmann, J.; Amonette, J.E.; Roberts, K.; et al. Role of biochar in mitigation of climate change. In *Handbook of Climate Change and Agroecosystems: Impacts, Adaptation, and Mitigation*; Imperial College Press: London, UK, 2010; pp. 343–363.
40. Xie, T.; Sadasivam, B.Y.; Reddy, K.R.; et al. Review of the effects of biochar amendment on soil properties and carbon sequestration. *J. Hazard. Toxic Radioact. Waste* **2016**, *20*, 04015013. [CrossRef]
41. Rehman, H.A.; Razzaq, R. Benefits of biochar on the agriculture and environment—A review. *J. Environ. Anal. Chem.* **2017**, *4*, 3. [CrossRef]
42. Karan, S.K.; Woolf, D.; Azzi, E.S.; et al. Potential for biochar carbon sequestration from crop residues: A global spatially explicit assessment. *GCB Bioenergy* **2023**, *15*, 1424–1436. [CrossRef]
43. Bopp, C.; Engler, A.; Poortvliet, P.M.; et al. The role of farmers' intrinsic motivation in the effectiveness of policy incentives to promote sustainable agricultural practices. *J. Environ. Manag.* **2019**, *244*, 320–327. [CrossRef]
44. Sanchez-Reinoso, A.D.; Ávila-Pedraza, E.A.; Restrepo-Díaz, H. Use of biochar in agriculture. *Acta Biol. Colomb.* **2020**, *25*, 327–338. [CrossRef]
45. Mishra, A.; Gupta, B.; Kumar, N.; et al. Synthesis of calcite-based bio-composite biochar for enhanced biosorption and detoxification of chromium Cr (VI) by *Zhihengliuella* sp. ISTPL4. *Bioresour. Technol.* **2020**, *307*, 123262. [CrossRef]
46. Yadav, S.P.S.; Bhandari, S.; Bhatta, D.; et al. Biochar application: A sustainable approach to improve soil health. *J. Agric. Food Res.* **2023**, *11*, 100498. [CrossRef]
47. Spokas, K.A.; Cantrell, K.B.; Novak, J.M.; et al. Biochar: A synthesis of its agronomic impact beyond carbon sequestration. *J. Environ. Qual.* **2012**, *41*, 973–989. [CrossRef]
48. Allohverdi, T.; Mohanty, A.K.; Roy, P.; et al. A review on current status of biochar uses in agriculture. *Molecules* **2021**, *26*, 5584. [CrossRef]
49. Sahota, S.; Vijay, V.K.; Subbarao, P.M.V.; et al. Characterization of leaf waste based biochar for cost effective hydrogen sulphide removal from biogas. *Bioresour. Technol.* **2018**, *250*, 635–641. [CrossRef]
50. Rubin, R.; Oldfield, E.; Lavallee, J.; et al. Climate mitigation through soil amendments: Quantification, evidence, and uncertainty. *Carbon Manag.* **2023**, *14*, 2217785. [CrossRef]
51. Jat, M.L.; Chakraborty, D.; Ladha, J.K.; et al. Carbon sequestration potential, challenges, and strategies towards climate action in smallholder agricultural systems of South Asia. *Crop Environ.* **2022**, *1*, 86–101. [CrossRef]
52. Mekuria, W.; Noble, A. The role of biochar in ameliorating disturbed soils and sequestering soil carbon in tropical agricultural production systems. *Appl. Environ. Soil Sci.* **2013**, 1–10. [CrossRef]
53. Xiao, C. *Soil Organic Carbon Storage (Sequestration) Principles and Management: Potential Role for Recycled Organic Materials in Agricultural Soils of Washington State*; Washington Department of Ecology: Olympia, WA, USA, 2015.

54. Keskinen, R.; Hyväluoma, J.; Sohlo, L.; et al. Fertilizer and soil conditioner value of broiler manure biochars. *Biochar* **2019**, *1*, 259–270. [CrossRef]
55. Gupta, D.K.; Gupta, C.K.; Dubey, R.; et al. Role of biochar in carbon sequestration and greenhouse gas mitigation. In *Biochar Applications in Agriculture and Environment Management*; Springer: Cham, Switzerland, 2020; pp. 141–165. [CrossRef]
56. Bolster, C.H. Role of sand size on bacterial retention in biochar-amended sand filters. *Biochar* **2019**, *1*, 353–363. [CrossRef]
57. Safari, S.; von Gunten, K.; Alam, M.S.; et al. Biochar colloids and their use in contaminants removal. *Biochar* **2019**, *1*, 151–162. [CrossRef]
58. Duan, W.; Oleszczuk, P.; Pan, B.; et al. Environmental behavior of engineered biochars and their aging processes in soil. *Biochar* **2019**, *1*, 339–351. [CrossRef]
59. Lehmann, J. Science-to-action through global and regional biochar networks. *Biochar* **2019**, *1*, 337. [CrossRef]
60. Yadav, R.K.; Yadav, M.R.; Kumar, R.; et al. Role of biochar in mitigation of climate change through carbon sequestration. *Int. J. Curr. Microbiol. App. Sci.* **2017**, *6*, 859–866. [CrossRef]
61. Gunarathne, V.; Senadeera, A.; Gunarathne, U.; et al. Potential of biochar and organic amendments for reclamation of coastal acidic-salt affected soil. *Biochar* **2020**, *2*, 107–120. [CrossRef]
62. Hussin, F.; Rahim, S.A.N.M.; Hatta, N.S.M.; et al. A systematic review of machine learning approaches in carbon capture applications. *J. CO_2 Util.* **2023**, *71*, 102474. [CrossRef]
63. Ukoba, K.; Jen, T.C. Biochar and application of machine learning: A review. In *Biochar-Productive Technologies, Properties and Application*; IntechOpen: London, UK, 2022. [CrossRef]
64. Garcia-Jaramillo, M.; Meyer, K.M.; Phillips, C.L.; et al. Biochar addition to vineyard soils: effects on soil functions, grape yield and wine quality. *Biochar* **2021**, *3*, 565–577. [CrossRef]
65. Yan, Y.; Borhani, T.N.; Subraveti, S.G.; et al. Harnessing the power of machine learning for carbon capture, utilisation, and storage (CCUS): A state-of-the-art review. *Energy Environ. Sci.* **2021**, *14*, 6122–6157. [CrossRef]
66. Jiao, Y.; Li, D.; Wang, M.; et al. A scientometric review of biochar preparation research from 2006 to 2019. *Biochar* **2021**, *3*, 283–298. [CrossRef]
67. Natcvetova, A. The Role of Artificial Intelligence in Measuring and Modelling Soil Organic Carbon in Agricultural Lands. Master's Thesis, Lahti University of Technology LUT, Lappeenranta, Finland, 2021.
68. Xie, S.; Yu, G.; Jiang, R.; et al. Moderate sewage sludge biochar application on alkaline soil for corn growth: A field study. *Biochar* **2021**, *3*, 135–147. [CrossRef]
69. Li, T.; Xia, A.; McLaren, T.I.; et al. Preliminary results in innovative solutions for soil carbon estimation: integrating remote sensing, machine learning, and proximal sensing spectroscopy. *Remote Sens.* **2023**, *15*, 5571. [CrossRef]
70. Grunwald, S. Artificial intelligence and soil carbon modeling demystified: Power, potentials, and perils. *Carbon Footprints* **2022**, *1*, 5. [CrossRef]
71. Pietris, J.; Lam, A.; Bacchi, S.; et al. Health economic implications of artificial intelligence implementation for ophthalmology in Australia: A systematic review. *Asia-Pac. J. Ophthalmol.* **2022**, *11*, 554–562.
72. Li, Y.; Gupta, R.; You, S. Machine learning assisted prediction of biochar yield and composition via pyrolysis of biomass. *Bioresour. Technol.* **2022**, *359*, 127511. [CrossRef]
73. Wu, P.; Ata-Ul-Karim, S.T.; Singh, B.P.; et al. A scientometric review of biochar research in the past 20 years (1998–2018). *Biochar* **2019**, *1*, 23–43. [CrossRef]
74. Zhu, X.; Li, Y.; Wang, X. Machine learning prediction of biochar yield and carbon contents in biochar based on biomass characteristics and pyrolysis conditions. *Bioresour. Technol.* **2019**, *288*, 121527. [CrossRef]
75. Kumar, V.; Thakur, I.S. Biodiesel production from transesterification of Serratia sp. ISTD04 lipids using immobilised lipase on biocomposite materials of biomineralized products of carbon dioxide sequestrating bacterium. *Bioresour. Technol.* **2020**, *307*, 123193. [CrossRef]
76. Shao, Y.; Long, Y.; Wang, H.; et al. Hydrochar derived from green waste by microwave hydrothermal carbonization. *Renew. Energy* **2019**, *135*, 1327–1334. [CrossRef]
77. Xiang, W.; Zhang, X.; Chen, J.; et al. Biochar technology in wastewater treatment: A critical review. *Chemosphere* **2020**, *252*, 126539. [CrossRef]
78. Safarian, S. Performance analysis of sustainable technologies for biochar production: A comprehensive review. *Energy Rep.* **2023**, *9*, 4574–4593. [CrossRef]
79. Amoah-Antwi, C.; Kwiatkowska-Malina, J.; Thornton, S.F.; et al. Restoration of soil quality using biochar and brown coal waste: A review. *Sci. Total Environ.* **2020**, *722*, 137852. [CrossRef]
80. Piñeiro, V.; Arias, J.; Dürr, J.; et al. A scoping review on incentives for adoption of sustainable agricultural

practices and their outcomes. *Nat. Sustain.* **2020**, *3*, 809–820. [CrossRef]
81. Ameloot, N.; Sleutel, S.; Case, S.D.; et al. C mineralization and microbial activity in four biochar field experiments several years after incorporation. *Soil Biol. Biochem.* **2014**, *78*, 195–203. [CrossRef]
82. Ali, A.; Guo, D.; Jeyasundar, P.G.S.A.; et al. Application of wood biochar in polluted soils stabilized the toxic metals and enhanced wheat (*Triticum aestivum*) growth and soil enzymatic activity. *Ecotoxicol. Environ. Saf.* **2019**, *184*, 109635. [CrossRef]
83. Aziz, S.; Ali, M.I.; Farooq, U.; et al. Enhanced bioremediation of diesel range hydrocarbons in soil using biochar made from organic wastes. *Environ. Monit. Assess.* **2020**, *192*, 569. [CrossRef]
84. Awasthi, M.K.; Awasthi, S.K.; Wang, Q.; et al. Influence of biochar on volatile fatty acids accumulation and microbial community succession during biosolid composting. *Bioresour. Technol.* **2018**, *251*, 158–164. [CrossRef]
85. Bolan, N.; Kumar, M.; Singh, E.; et al. Antimony contamination and its risk management in complex environmental settings: A review. *Environ. Int.* **2022**, *158*, 106908. [CrossRef]
86. Awasthi, M.K. Engineered biochar: A multifunctional material for energy and environment. *Environ. Pollut.* **2022**, *298*, 118831. [CrossRef]
87. Das, O.; Sarmah, A.K.; Bhattacharyya, D. Structure–mechanics property relationship of waste derived biochars. *Sci. Total Environ.* **2015**, *538*, 611–620. [CrossRef]
88. He, J.; Li, Y.; Qi, H.; et al. Biochar amendment changed soil-bound fractions of silver nanoparticles and ions but not their uptake by radish at an environmentally relevant concentration. *Biochar* **2020**, *2*, 307–317. [CrossRef]
89. Jagaba, A.H.; Kutty, S.R.M.; Abubakar, S.; et al. Synthesis, characterization, and performance evaluation of hybrid waste sludge biochar for COD and color removal from agro-industrial effluent. *Separations* **2022**, *9*, 258. [CrossRef]
90. Majeed, Y.; Khan, M.U.; Waseem, M.; et al. Renewable energy as an alternative source for energy management in agriculture. *Energy Rep.* **2023**, *10*, 344–359. [CrossRef]