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Review

Potential of biochar g-C_3N_4 nanocomposites in soil remediation of 2,4-D with mechanistic insights and future prospects

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Received: 18 July 2025 / Accepted: 21 October 2025
Published online: 22 October 2025

Abstract
The widespread application of herbicides, particularly 2,4-dichlorophenoxyacetic acid (2,4-D), has raised serious concerns due to its persistence in soil and water, posing significant risks to environmental and human health. This review explores the potential of biochar/graphitic carbon nitride (g-C_3N_4) nanocomposites as a promising solution for remediating 2,4-D-contaminated soils. The synergistic combination of biochar's high surface area and g-C_3N_4's photocatalytic properties enables dual-action remediation via adsorption and photodegradation. Key operational parameters, such as nanocomposite dosage, contact time, and initial pollutant concentration, substantially affect removal efficiency. While laboratory studies demonstrate high potential, field-scale implementation remains limited due to challenges including UV light dependency, energy-intensive biochar production, surface fouling, and microbial degradation. Additionally, the long-term ecological impacts of g-C_3N_4 in soil environments remain underexplored. Integrating these nanocomposites with sustainable agricultural practices and biocontrol methods may improve applicability. Future research should prioritize scalability, environmental safety, and cost-effectiveness to support wider adoption. Clinical trial number: not applicable.

Keywords 2,4-D degradation · Biochar/g-C_3N_4 nanocomposites · Photocatalysis · Soil remediation · Environmental safety

1 Introduction

The widespread use of herbicides in agriculture has led to significant environmental challenges, particularly in soil and water systems [1]. Among these herbicides, 2,4-dichlorophenoxyacetic acid (2,4-D) remains one of the most extensively used synthetic auxins due to its low cost and high efficacy [2]. However, its persistence in soil, with a half-life ranging from 20 to over 300 days, raises serious concerns regarding ecological safety and human health [3]. Prolonged exposure to 2,4-D has been linked to endocrine disruption, mutagenicity, and potential carcinogenicity, making the remediation of contaminated soils a critical environmental priority [4].

Several remediation strategies have been developed to address 2,4-D contamination in soils, including bioremediation, chemical oxidation, and phytoremediation [5–7]. While these approaches offer varying degrees of success, they often suffer from limitations such as incomplete degradation, long treatment durations, and secondary pollution [8–10]. These challenges underscore the need for more effective, scalable, and environmentally benign alternatives.

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Biochar-based nanocomposites, particularly those incorporating graphitic carbon nitride (g-C_3N_4), have emerged as promising materials for environmental remediation due to their combined physicochemical properties. Biochar offers a high surface area, porous structure, and abundant functional groups for pollutant adsorption, while g-C_3N_4 contributes visible-light-driven photocatalytic activity capable of degrading organic contaminants [11, 12]. Although both materials have individually shown promise in soil remediation and water treatment, their integration into a single nanocomposite system specifically for 2,4-D remediation in soils has not yet been extensively studied.

This review aims to critically assess the theoretical and practical potential of biochar/g-C_3N_4 nanocomposites for the remediation of 2,4-D-contaminated soils. Previous reviews have examined biochar for soil remediation (e.g., Twagirayezu, Gratien, et al. [13], Cara, Irina Gabriela, et al. [14]), and g-C_3N_4 as a photocatalyst for environmental pollutants (e.g., Zheng et al. [15], Feng et al. [16]), yet there is currently no comprehensive evaluation of their combined use as nanocomposites for herbicide-contaminated soils. By focusing on the synergistic integration of adsorption (via biochar) and photocatalysis (via g-C_3N_4), this review highlights the prospective potential of these nanocomposites to enhance 2,4-D degradation in soil systems. We synthesize the current understanding of their individual and combined properties, delineate removal mechanisms, evaluate synthesis and characterization strategies, and discuss key operational factors influencing performance. By identifying critical research gaps, technical limitations, and future directions, this work provides a timely perspective to guide the development of biochar/g-C_3N_4 nanocomposites toward field-scale applications in soil remediation.

2 Literature search strategy

Relevant literature was collected from academic databases including Web of Science, Scopus, and ScienceDirect using keywords such as "2,4-D degradation," "biochar nanocomposites," "g-C_3N_4 photocatalysis," and "soil remediation." The selection focused primarily on peer-reviewed journal articles, reviews, and recent experimental studies. The search prioritized publications from 2018 to 2025, with special emphasis on recent work (2023–2025), reflecting rapid advancements in photocatalytic and nanocomposite-based remediation. Foundational studies from 2011–2022 were also included to provide scientific context and background. Articles were chosen based on topical relevance, methodological rigor, and citation impact. Two references were undated but included due to their thematic alignment and scholarly credibility.

3 Environmental relevance of 2,4-D and the need for soil remediation

3.1 4-D as a pesticide

2,4-Dichlorophenoxyacetic acid (2,4-D) is a widely used phenoxy herbicide that selectively targets broadleaf weeds by mimicking auxins, plant hormones that regulate growth [17, 18]. This disruption leads to abnormal cell elongation and ultimately plant death [19]. Its selectivity allows for effective weed control in monocot crops such as cereals, making it a staple in global agriculture [20]. Since its introduction in the 1940s, 2,4-D has remained popular due to its efficacy, affordability, and versatility across crops like wheat, corn, rice, and sugarcane [21, 22]. It is available in various formulations, acid, salts, and esters, designed to optimize application and environmental stability [9]. However, its widespread use has raised concerns about environmental persistence and herbicide resistance, emphasizing the need for advanced remediation strategies to mitigate its impact.

3.2 Health risks associated with 2,4-D exposure

2,4-D is classified as a Group 2B carcinogen by the International Agency for Research on Cancer (IARC), indicating possible carcinogenicity in humans [17]. Acute exposure may cause skin and eye irritation, respiratory symptoms, and gastrointestinal distress [18–20]. Systemic effects such as headaches and fatigue suggest potential neurological involvement. Chronic exposure is linked to endocrine disruption, reproductive toxicity, and organ damage, though findings remain under investigation [21–23]. In plants, 2,4-D disrupts hormonal balance, causing epinasty and growth abnormalities that reduce crop vigor and yield [9]. These toxicological concerns underscore the need for targeted remediation strategies to minimize risks to human health and ecological systems [24].

The chemical structure of 2,4-D consists of a chlorinated aromatic ring attached to an acetic acid moiety. The presence of two chlorine atoms at the 2 and 4 positions of the phenyl ring enhances its lipophilicity and environmental persistence, contributing to bioaccumulation and prolonged exposure risks [25]. The phenoxyacetic acid group mimics natural plant auxins, disrupting hormonal signaling in both plants and potentially in mammalian endocrine systems [26]. This structural mimicry is central to its herbicidal action but also raises concerns about off-target effects in humans, particularly regarding endocrine and reproductive toxicity [27]. Understanding this structure–activity relationship helps clarify the molecular basis of 2,4-D's toxicological profile and supports the need for cautious handling and regulatory oversight.

3.3 Environmental impacts of 2,4-D in soil systems

2,4-D's persistence and mobility in soil and water systems raise significant environmental concerns [1]. It undergoes runoff, leaching, volatilization, and microbial degradation, influencing its fate and transport [28]. In soil, 2,4-D reduces organic matter, disrupts microbial communities, and harms beneficial fauna like earthworms, leading to impaired fertility and structure [29, 30]. Its retention varies with soil conditions, and high solubility increases the risk of aquatic contamination [31]. Bioaccumulation in aquatic organisms further amplifies ecological and human health risks [32]. These impacts highlight the urgency of developing efficient nanocomposite-based remediation technologies.

4 Properties and potential of biochar/g-C_3N_4 nanocomposites

4.1 Properties and benefits of biochar in soil remediation and amendment

Biochar, a carbon-rich material produced through the pyrolysis of biomass at temperatures ranging from 350 to 900 °C in a low-oxygen environment, has gained attention for its environmental and agricultural applications [33]. Its high surface area, pore diameter, pore volume, and porosity enable effective adsorption of pollutants, making it a promising material for air treatment, where it can capture volatile organic compounds (VOCs), particulate matter, and carbon dioxide [34]. In water and wastewater treatment, biochar has been shown to remove micropollutants, including heavy metals and organic contaminants, through its high adsorption capacity and functional groups (e.g., carboxyl and hydroxyl groups) [35]. Studies have demonstrated its ability to mitigate the effects of toxic substances such as pesticides and herbicides in soils, reducing their bioavailability and preventing further contamination. Chemical activation of biochar using agents such as $ZnCl_2$ and KOH has been shown to dramatically enhance surface area, porosity, and functional group density, thereby improving adsorption capacity for various pollutants, including heavy metals and organic contaminants [36]. As a soil amendment, biochar improves soil fertility, especially in nutrient-deficient or acidic soils, by enhancing water retention, increasing cation-exchange capacity (CEC), and promoting microbial activity [35]. Moreover, its incorporation into soil increases long-term organic matter content, fostering sustainable agricultural practices while contributing to carbon sequestration.

Biochar is effective in adsorbing a wide range of pollutants, including herbicides like 2,4-dichlorophenoxyacetic acid (2,4-D) [37]. In soil and water treatment, biochar can reduce the bioavailability of herbicides, thereby mitigating their adverse effects on soil health and preventing the leaching of these toxic compounds into groundwater [38]. By immobilizing herbicides within their porous structure, biochar reduces their mobility and facilitates their breakdown by soil microbes, which may otherwise be inhibited by herbicide toxicity [39]. Furthermore, biochar enhances soil fertility by improving water retention, nutrient availability, and microbial activity, which collectively support agricultural sustainability and reduce the long-term environmental impact of herbicide application [40]. Despite these advantages, biochar's effectiveness in herbicide remediation is contingent upon factors such as feedstock type and pyrolysis conditions (particle size, activation temperature, activation time, and heating rate), necessitating further research to optimize its use across different environmental contexts.

4.2 Characteristics of g-C_3N_4 and its applications in soil remediation and amendment

Graphitic carbon nitride (g-C_3N_4), a polymeric material composed of tri-s-triazine units, has attracted significant attention for its environmental applications, driven by its outstanding physicochemical properties, including high chemical stability, tunable electronic characteristics, and exceptional photocatalytic activity [41]. These attributes make g-C_3N_4 a versatile material in soil remediation, particularly for the degradation of persistent organic pollutants, such as herbicides and industrial contaminants [42]. In particular, g-C_3N_4 has potential in the photodegradation of 2,4-D, a widely used herbicide that persists in soils, posing significant environmental risks. Although research into the direct degradation of

2,4-D by g-C_3N_4 is still in its early stages, its ability to utilize visible light for photocatalytic reactions suggests its promising role in enhancing the breakdown of this pollutant [41]. The photocatalytic properties of g-C_3N_4, combined with its ability to generate reactive oxygen species under ambient light conditions, make it an ideal candidate for addressing herbicide contamination in soils [43].

Beyond pollutant degradation, g-C_3N_4 holds significant potential for amending infertile soils. Its high surface area, chemical stability, and ability to capture visible light allow it to interact effectively with soil components, promoting nutrient cycling and enhancing soil health [44]. In nitrogen-deficient soils, g-C_3N_4 has been shown to facilitate photocatalytic nitrogen fixation, converting atmospheric nitrogen into bioavailable forms, thereby enhancing soil fertility [44]. Additionally, g-C_3N_4 improves soil properties by increasing water retention capacity and supporting microbial activity, both of which are crucial for restoring degraded soils [41]. Furthermore, its capacity to adsorb toxic heavy metals from contaminated soils further enhances its role as a soil amendment, contributing to soil detoxification and the restoration of healthy, productive soils. The multifunctional capabilities of g-C_3N_4, spanning from pollutant degradation to soil nutrient enhancement, highlight its potential as a sustainable material for managing both herbicide-contaminated and infertile soils [45]. Continued research is essential to fully understand the long-term effects of g-C_3N_4 on soil structure and fertility, as well as its potential synergy with other soil amendments to maximize its benefits in diverse soil environments.

4.3 Synergistic effects of biochar/g-C_3N_4 nanocomposites

Biochar and g-C_3N_4 each have distinct properties for adsorbing and degrading pollutants. However, their combination results in synergistic effects that significantly enhance the overall performance of the nanocomposite in environmental remediation [46, 47]. Biochar provides a stable support structure, preserving the surface area and porosity, while g-C_3N_4 contributes photocatalytic activity, enabling the degradation of organic pollutants, such as 2,4-D, under light exposure [48, 49]. The synergy arises from the enhanced adsorption properties due to the combined functional groups on both materials and the ability of g-C_3N_4 to activate reactive oxygen species (ROS) that facilitate further degradation of pollutants [50]. This dual-action mechanism increases the efficiency and sustainability of the nanocomposite for herbicide remediation, thus mitigating the environmental impacts of chemical herbicides.

5 Mechanisms of 2,4-D remediation using biochar/g-C_3N_4 nanocomposites

The combination of biochar and graphitic carbon nitride (g-C_3N_4) nanomaterials for the remediation of organic pollutants has garnered increasing attention in recent years [51–53]. The biochar/g-C_3N_4 nanocomposite exhibits a unique synergy that significantly improves the adsorption and degradation of herbicides, particularly compared to biochar alone. The adsorption mechanisms of 2,4-D are governed by both physical and chemical interactions between the herbicide and the nanocomposite [54, 55]. Physically, the large surface area and high porosity of biochar provide ample sites for hydrophobic interactions, van der Waals forces, and π-π stacking with the aromatic herbicide molecules, facilitating their physical adsorption [56]. Chemically, the functional groups on biochar (such as carboxyl, hydroxyl, and phenolic groups) and surface modifications on g-C_3N_4 (e.g., amino groups) promote electrostatic interactions and hydrogen bonding with 2,4-D, thus enhancing its chemical adsorption [44, 54]. This reduces the bioavailability of 2,4-D, preventing its mobility and mitigating its toxic effects on soil and groundwater. Moreover, the intimate contact between biochar and g-C_3N_4 facilitates interfacial charge transfer, which plays a crucial role in enhancing photocatalytic efficiency. Biochar acts as an electron acceptor and transporter, suppressing the recombination of photogenerated electron–hole pairs in g-C_3N_4 and thereby prolonging the lifetime of charge carriers. This synergistic interaction boosts the generation of reactive oxygen species and improves the overall degradation kinetics.

In addition to adsorption, the biochar/g-C_3N_4 nanocomposite promotes the photocatalytic degradation of 2,4-D, providing a dual-mechanism approach for herbicide remediation [57]. Under UV light exposure, the g-C_3N_4 component activates to generate reactive oxygen species (ROS), such as hydroxyl radicals (•OH) and superoxide anions ($O_2^{\bullet-}$) [58]. These ROS initiate the oxidative degradation of 2,4-D, breaking it down into less harmful byproducts.

The photocatalytic process involves the excitation of g-C_3N_4 under UV light, where electrons (e^-) in the valence band are promoted to the conduction band, leaving behind holes (h^+). These photogenerated electrons and holes participate in redox reactions: electrons reduce O_2 to form $O_2\bullet-$, while holes oxidize H_2O or OH^- to generate •OH radicals. These ROS attack the 2,4-D molecules, leading to cleavage of the aromatic ring and formation of intermediate compounds such as hydroquinone, catechol, and eventually CO_2 and H_2O. As shown in Fig. 1, this mechanism illustrates the dual role of the nanocomposite, where biochar enhances adsorption and electron mobility, while g-C_3N_4 drives photocatalytic degradation through ROS generation and electron–hole transfer.

The photocatalytic activity of g-C_3N_4 enhances the overall remediation process, accelerating the degradation of herbicides, particularly under light exposure [59]. The biochar component serves a dual function: it not only maintains high surface area and porosity for enhanced adsorption but also provides a stable support for g-C_3N_4, ensuring optimal contact between the herbicide and the catalytic sites. The nanostructures of g-C_3N_4 further enhance the efficiency of these interactions by increasing the availability of active sites for adsorption and degradation. This synergy between biochar and g-C_3N_4 not only improves photocatalytic performance but also contributes to structural stability, enhanced light absorption, and better dispersion of g-C_3N_4 particles. Together, biochar and g-C_3N_4 form a highly effective composite that not only adsorbs and detoxifies herbicides but also supports the restoration of soil health by reducing herbicide toxicity and contributing to overall environmental sustainability. Ongoing research into optimizing the application of biochar/g-C_3N_4 nanocomposites (e.g., adjusting nanocomposite dose, incubation time, and initial 2,4-D concentration) is essential for maximizing their potential in soil treatment.

6 Synthesis and characterization of biochar/g-C_3N_4 nanocomposites

6.1 Method of biochar synthesis

In the synthesis of biochar, thermal activation is the primary method used due to its efficiency, scalability, and cost-effectiveness [60]. This process, commonly referred to as pyrolysis, involves the heating of organic feedstock at temperatures typically ranging from 350 to 900 °C in an oxygen-limited or inert atmosphere [61]. Thermal activation results in a carbon-rich material with a highly stable structure, characterized by a porous texture and a high surface area. These properties make biochar produced via thermal activation suitable for various applications, particularly in soil treatment, amendment, and environmental remediation [62].

While thermal activation predominates in biochar production, chemical activation is occasionally employed in specific contexts to further enhance the biochar's porosity and surface area [63]. In this method, biomass is treated with chemicals such as zinc chloride ($ZnCl_2$), potassium hydroxide (KOH), or nitric acid (HNO_3), followed by heating at lower temperatures (typically 400–600 °C) [64–66]. This results in biochar with enhanced adsorption capacities, which can be beneficial for applications like water treatment and air purification. However, chemical activation is not commonly utilized; most research conducted on biochar synthesis focuses on the more commonly employed thermal activation method. The carbonization process is typically carried out in an inert atmosphere, often using nitrogen (N_2) or helium (He), to prevent oxidation and minimize the ash content in the final product [67]. The inert environment ensures that non-carbon residues are effectively removed during thermal decomposition, leading to the formation of a porous carbon structure that is stable and suitable for various applications.

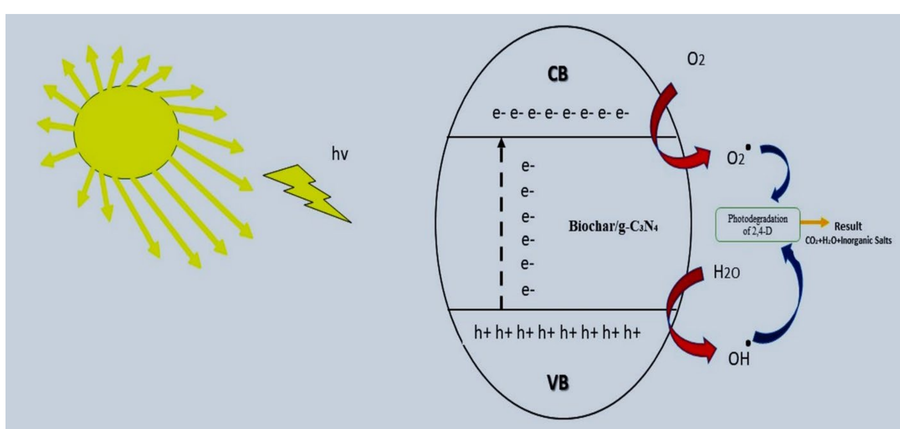

Fig. 1 Mechanism of 2,4-D photodegradation

6.2 Method of g-C_3N_4 synthesis

Graphitic carbon nitride (g-C_3N_4) has attracted significant attention for its potential applications in photocatalysis, energy storage, and sensing due to its unique electronic structure, high stability, and tunable properties [68]. Several synthetic approaches have been developed to prepare g-C_3N_4, each influencing its structure, surface area, and reactivity. The most commonly employed method is the thermal condensation of nitrogen-rich precursors, such as urea, melamine, and cyanamide, under controlled conditions [69]. This process typically involves heating the precursor in an alumina crucible at temperatures ranging from 500 to 600 °C [41]. For instance, urea-derived g-C_3N_4 is synthesized by heating urea at a rate of 5 °C/min to 550 °C, followed by a prolonged hold to ensure complete polymerization and the formation of the g-C_3N_4 framework [70]. The resulting solid is then cooled, ground into a fine powder, and used in subsequent applications. Similarly, melamine-based g-C_3N_4 is synthesized by calcining melamine at elevated temperatures (typically between 520 and 550 °C) under nitrogen or inert atmospheres to prevent excessive oxidation [71]. The advantage of melamine over urea lies in its higher nitrogen content, which can potentially enhance the photocatalytic activity of the final product.

In addition to these conventional methods, more advanced approaches such as high-temperature calcination with post-exfoliation treatments are gaining interest for enhancing the properties of g-C_3N_4 [72]. For example, exfoliation treatments involving sonication in acidic or basic solutions have been used to increase surface area and improve dispersion. These treatments can also tailor the electronic properties of g-C_3N_4, making it more suitable for various catalytic and energy-related applications [73]. Moreover, the introduction of dopants or co-catalysts during the synthesis process, such as metals or metal oxides, can further improve the material's photocatalytic efficiency by facilitating charge separation. Techniques like hydrothermal and sol–gel methods are also employed to obtain g-C_3N_4 with well-defined nanostructures, which are beneficial for applications in water splitting and CO_2 reduction [69]. Despite the extensive research on these synthesis methods, challenges remain in scaling up the production while maintaining uniformity in particle size, surface area, and crystallinity.

6.3 Method of BC/g-C_3N_4 nanocomposite synthesis methods

The development of BC/g-C_3N_4 nanocomposites has garnered considerable interest in recent years, particularly in the fields of environmental remediation, energy storage, and photocatalysis [41, 74]. These composites combine the advantageous properties of g-C_3N_4, such as its excellent photocatalytic activity, with the high surface area and porous nature of biochar, derived from various biomass sources. The synthesis of BC/g-C_3N_4 nanocomposites is typically achieved through physical mixing, sol–gel, or pyrolytic methods, each offering distinct advantages depending on the desired properties of the final product [74, 75].

One of the most commonly employed methods for fabricating BC/g-C_3N_4 composites is simple physical blending and ball milling [76]. The prepared biochar is mixed with g-C_3N_4 either through basic physical blending or more advanced techniques, such as ball milling. In the ball milling process, the biochar and g-C_3N_4 are ground together for several hours, resulting in a uniform dispersion of the two components and enhanced interaction between them. The addition of g-C_3N_4 improves the photocatalytic and electronic properties of biochar by providing active sites for reactions and facilitating charge transfer [74].

Alternatively, sol–gel and hydrothermal methods have been explored for the synthesis of BC/g-C_3N_4 composites, where g-C_3N_4 is typically synthesized first, followed by the incorporation of biochar. In the sol–gel method, precursor solutions containing both g-C_3N_4 and biochar are mixed and subjected to a gelation process under controlled conditions, followed by calcination to form the composite [41]. This approach allows for precise control over the size and distribution of g-C_3N_4 within the biochar matrix. Another method involves incorporating biochar during the synthesis of g-C_3N_4, where biochar is added to the precursor solution before calcination [41]. This ensures the in-situ formation of g-C_3N_4 in close proximity to the biochar, which can enhance the structural integrity and performance of the composite.

Overall, the synthesis of BC/g-C_3N_4 nanocomposites via these methods offers a versatile and cost-effective route to enhance the functionality of both materials. The key factors influencing the performance of the composites include the ratio of g-C_3N_4 to biochar, the calcination temperature, and the presence of dopants or co-catalysts.

6.4 Characterization techniques of the BC/g-C_3N_4 nanocomposite

The BC/g-C_3N_4 nanocomposite undergoes a range of characterization techniques to evaluate its physicochemical properties, ensuring its suitability for the effective treatment of 2,4-D contaminated soil. Proximate and ultimate analyses are foundational in providing a comprehensive understanding of the material's thermal stability and elemental composition [77]. The proximate analysis, which measures parameters such as moisture content, volatile matter, ash content, and fixed carbon, plays a critical role in determining the material's thermal behavior and combustion characteristics [78]. These factors are essential for assessing the material's performance under varying environmental conditions, such as those encountered in soil remediation. Ultimate analysis, on the other hand, provides a detailed elemental composition of the nanocomposite, shedding light on the carbon, hydrogen, nitrogen, and oxygen content, all of which influence the composite's reactivity and its capacity to degrade organic contaminants like 2,4-D [79].

To explore the surface morphology and pore structure of the composite, scanning electron microscopy (SEM) is employed [79]. This technique offers high-resolution imaging of the nanocomposite's surface, allowing for an in-depth examination of the dispersion of g-C_3N_4 within the biochar matrix. The structural features observed via SEM are directly linked to the material's performance, particularly in terms of enhancing adsorption capacity [80]. The presence of well-defined pores and a developed surface structure facilitates the interaction between the nanocomposite and pollutants such as 2,4-D, improving both the adsorption and catalytic degradation processes essential for effective soil remediation. Furthermore, X-ray diffraction (XRD) is utilized to assess the crystalline and amorphous nature of the composite, as well as its mineral composition [81]. The crystallinity of g-C_3N_4, a key component of the composite, significantly impacts its photocatalytic properties, which are vital for the breakdown of organic pollutants. XRD analysis also provides valuable information regarding the mineralogical content, which can influence the material's interaction with the contaminant and the soil matrix [82].

Fourier-transform infrared (FTIR) spectroscopy is used to identify the functional groups present on the surface of the nanocomposite [83]. This technique is crucial for detecting specific chemical bonds and functional groups, such as hydroxyl, carboxyl, and amino groups, which are integral to the composite's reactivity. These groups not only enhance the adsorption of 2,4-D but also facilitate the catalytic breakdown of contaminants, contributing to the overall efficacy of the material in environmental applications [84]. The surface area and porosity of the nanocomposite are determined using Brunauer–Emmett–Teller (BET) analysis, a method essential for evaluating the adsorption capacity of the composite [85]. A high surface area and optimized porosity are critical for ensuring efficient contact between the composite and contaminants in soil, thereby enhancing its ability to adsorb and degrade 2,4-D molecules.

Thermogravimetric analysis (TGA) assesses the thermal stability of the nanocomposite by monitoring its weight loss as a function of temperature [86]. This analysis is vital for determining the material's heat resistance, which is a key factor in its long-term stability and performance in high-temperature environments, such as those that may be encountered during soil treatment [87]. The material's ability to withstand elevated temperatures without significant degradation is crucial for ensuring its durability over time in soil-based applications. Additionally, the point of zero charge (pH_{PZC}) is determined to understand the pH at which the surface charge of the nanocomposite becomes neutral. This property is significant for predicting how the nanocomposite behaves in different soil conditions, as the surface charge influences the adsorption of pollutants and cations [88]. A well-defined pH_{PZC} can help optimize the composite's performance under varying pH conditions typically found in contaminated soils.

The pH and electrical conductivity (EC) of the nanocomposite are also measured to assess its ionic behavior and stability in soil environments [89]. The pH affects the ionization of functional groups on the surface, which in turn influences the material's interaction with contaminants like 2,4-D. The EC, which indicates the ion concentration, provides insights into the material's ability to exchange ions and its overall ionic activity, both of which play a role in its effectiveness for contaminant removal [90]. The bulk density and cation exchange capacity (CEC) are determined to understand the material's chemical behavior in soil [91]. The bulk density, which reflects the packing of the material, influences its diffusion and interaction with contaminants. A lower bulk density often indicates better porosity and improved contact with pollutants in the soil matrix [92]. CEC is a critical parameter for assessing the nanocomposite's ability to retain and exchange cations, which is especially important for nutrient retention and the uptake of contaminants like 2,4-D [93].

To evaluate the optical properties relevant to photocatalytic activity, UV–Vis diffuse reflectance spectroscopy (DRS) is employed to determine the light absorption behavior and band gap energies of biochar, g-C_3N_4, and the BC/g-C_3N_4 nanocomposite [74]. The band gap of pristine g-C_3N_4 typically falls around 2.7 eV, enabling visible light absorption, while biochar may exhibit broadband absorption due to its carbonaceous nature. The nanocomposite often shows a red-shift in absorption edge and reduced band gap, indicating enhanced light harvesting capabilities [94]. These optical modifications are crucial for improving photocatalytic efficiency under natural or simulated solar irradiation. Additionally, photoluminescence (PL) spectroscopy is used to assess the recombination rate of photo-generated electron–hole pairs [95]. A lower PL intensity in the nanocomposite compared to pure g-C_3N_4 suggests suppressed recombination, which directly correlates with improved photocatalytic degradation of 2,4-D. Together, these characterization techniques provide a comprehensive understanding of the BC/g-C_3N_4 nanocomposite's properties, offering insights into its potential for treating 2,4-D contaminated soil.

7 Factors influencing the efficiency of 2,4-D remediation

The efficiency of soil remediation, particularly in the context of pesticide-contaminated soils, is influenced by various factors that impact the effectiveness of remediation strategies [96]. Soil pH is one of the critical parameters, as it governs the acidity or alkalinity of the soil environment, which in turn affects the adsorption capacity of the adsorbent [97]. The electrostatic interactions between the adsorbent and the adsorbate (in this case, 2,4-D) are highly sensitive to pH [55]. A lower pH, characteristic of acidic conditions, can increase the positive charge on metal ions, enhancing adsorption, while a higher pH may increase the negative charge on the adsorbent, potentially reducing adsorption capacity. Moreover, pH significantly influences exchangeable acidity and the overall chemical dynamics in the soil, affecting the mobility and bioavailability of contaminants like 2,4-D [98]. This is particularly relevant when considering the use of nanocomposites for remediation, as the interaction between the nanomaterials and the contaminants is pH-dependent.

Electrical conductivity (EC) is another important factor that governs the remediation process. EC is a measure of the ionic strength in the soil solution and reflects the concentration of soluble inorganic ions [99]. Higher EC values indicate a higher concentration of soluble ions in the soil solution, which may compete with the adsorbate (2,4-D) for available active sites on the nanocomposite, thus reducing its adsorption capacity [100]. The Cation Exchange Capacity (CEC) of the soil is crucial because it determines the soil's ability to retain and exchange essential nutrients and contaminants [101]. An optimal EC level is necessary for effective remediation, as it ensures that the nanocomposite can function efficiently in terms of adsorption and photocatalysis. Excessively high EC can lead to competition between ions and the adsorbate for active sites, thereby reducing the nanocomposite's ability to remove contaminants [102]. Conversely, low EC may limit the ionic interactions necessary for effective remediation, potentially hindering the adsorption and photocatalytic processes [103].

In addition to the above-mentioned factors, the soil texture and organic matter content are often overlooked but play significant roles in the efficiency of remediation [104]. The presence of organic matter can enhance the adsorption of contaminants by providing additional binding sites, but it may also interact with the nanocomposites and affect their activity [105]. Specifically, naturally occurring organic compounds such as humic and fulvic acids can form complexes with 2,4-D or adsorb onto the surface of the nanocomposite, potentially blocking active sites and reducing photocatalytic efficiency [106]. These substances may also act as photosensitizers or radical scavengers, altering the generation and stability of reactive oxygen species (ROS) during photodegradation. Similarly, soil texture influences the mobility of contaminants and nanocomposites, with finer soils (such as clay) often retaining contaminants more effectively, whereas coarser soils may allow for greater mobility and diffusion [107]. The presence of competing cations (e.g., Ca^{2+}, Mg^{2+}, Na^{+}) and anions (e.g., NO_3^{-}, SO_4^{2-}) in the soil matrix can also interfere with the adsorption of 2,4-D by occupying active sites or altering surface charge dynamics [108]. These ions may reduce the electrostatic attraction between the nanocomposite and the target pollutant, thereby diminishing overall remediation efficiency.

The temperature and light intensity also impact the photocatalytic degradation process, as these factors influence the rate at which the photocatalyst generates reactive species [109]. This review paper assesses the impact of three primary variables on the efficiency of 2,4-D degradation and removal: nanocomposite dose, incubation time, and the initial concentration of 2,4-D in the contaminated soil. While several factors influence the overall remediation process, these three factors were selected to evaluate their specific contributions.

7.1 Nanocomposite dose

The nanocomposite dose applied is crucial in determining the remediation efficacy. The introduction of photocatalysts such as g-C_3N_4 into the soil facilitates the photodegradation of 2,4-D under light exposure [44]. The photocatalytic process generates reactive oxygen species (ROS), such as hydroxyl radicals, that degrade 2,4-D into non-toxic compounds. Moreover, the nanocomposite serves as an adsorbent, providing surface area for the physical adsorption of 2,4-D molecules [110]. However, the dose of nanocomposite must be optimized, as excessive amounts may lead to aggregation of the particles, reducing their available surface area and photocatalytic efficiency [111]. Furthermore, an overly high dose can result in the formation of secondary pollutants or interfere with the soil's natural properties, potentially hindering the overall remediation process.

7.2 Incubation time

Incubation time is another critical factor that influences the efficiency of the treatment process. Sufficient incubation time allows for the effective interaction between the nanocomposite, 2,4-D, and the soil matrix [112]. It ensures adequate photodegradation and adsorption of the contaminant. However, excessive incubation time can lead to the saturation of adsorption sites, at which point the nanocomposite becomes less effective [113]. Moreover, prolonged exposure may also lead to the leaching of degradation products, which could pose new environmental challenges. Therefore, there is an optimal incubation period that balances effective remediation without unnecessary accumulation of by-products or overuse of resources.

7.3 Initial 2,4-D concentration

The initial concentration of 2,4-D is a key parameter influencing the remediation process. At higher concentrations, the capacity of the nanocomposite to degrade and adsorb the contaminant may be overwhelmed, particularly if the adsorbent's surface area and photocatalytic activity are insufficient [114]. The initial concentration is a limiting factor in determining the maximum amount of 2,4-D that can be effectively treated with a given dose of nanocomposite within a specified incubation time. As the concentration of 2,4-D increases, the interaction between the contaminant and the nanocomposite becomes more complex, requiring a higher capacity for adsorption and degradation. Beyond an optimum concentration, the efficiency of both photocatalysis and adsorption may diminish due to saturation or excessive competition for active sites [74]. Therefore, a balance must be struck to ensure that the nanocomposite dose and incubation time are appropriately scaled to the initial contaminant load. Given these variables, it is essential to determine the optimal conditions for each factor to ensure that the remediation process is both effective and sustainable.

8 Comparison of remediation techniques for 2,4-D contaminated soil

Soil contamination is a pervasive environmental issue that requires effective remediation strategies to restore soil health and mitigate the impact of toxic pollutants [115]. Numerous methods have been developed to address contaminated soils, each with its strengths and limitations. This section provides a comparative analysis of different remediation strategies, focusing on their mechanisms, effectiveness, and constraints in the context of 2,4-D contamination.

Phytoremediation is a promising and environmentally friendly technique for remediating contaminated soils. It offers several advantages, including its cost-effectiveness, sustainability, and minimal environmental disruption [116]. Phytoremediation involves the use of plants to absorb, degrade, or immobilize contaminants from soil and water [117]. The primary mechanisms of phytoremediation include phytodegradation, where plants degrade contaminants through metabolic processes; phytovolatilization, where plants take up contaminants and release them into the atmosphere in a less harmful form; and rhizodegradation, where plant roots enhance microbial activity that breaks down pollutants. Additionally, phytostabilization and phytoextraction are widely recognized as two major phytoremediation mechanisms. Phytostabilization involves the immobilization of contaminants in the soil, preventing their spread, while phytoextraction involves the uptake and concentration of pollutants in plant tissues, which can later be harvested for disposal [118, 119]. Despite its potential, phytoremediation is often hindered by several limitations. The method typically requires long timeframes to achieve significant results, particularly for deep soil contaminants, and its effectiveness is highly contingent on factors such as plant species selection, root length, and contaminant type. Moreover, phytoremediation can be influenced by external factors such as climate conditions, pollutant-induced toxicity, and specific soil characteristics, all of which can limit its applicability in some environments [116].

Bioremediation, another widely used treatment method, utilizes microorganisms, such as bacteria, fungi, and algae, to degrade organic pollutants, including 2,4-D [120]. Microbial remediation mechanisms include bioaugmentation, where beneficial microbes are introduced to the contaminated site to enhance degradation, and bioventing, where microbial activity is stimulated by adjusting soil aeration [121]. The effectiveness of bioremediation largely depends on microbial adaptability and environmental factors such as pH, temperature, moisture, and nutrient availability

[122]. While bioremediation can be highly effective and environmentally benign, it tends to be a slow process and is highly site-dependent. Microbial degradation can be impeded by the presence of toxic pollutants, which may inhibit microbial activity or even lead to microbial toxicity. Furthermore, the rate of degradation may vary significantly across different environmental conditions, which can make the method unpredictable in certain settings [123].

Chemical remediation involves the use of various chemicals, such as oxidants (potassium permanganate, hydrogen peroxide), reducing agents (sodium dithionite, zerovalent iron), and surfactants (sodium dodecyl sulfate, rhamnolipids) to treat contaminated soil, specifically 2,4-D contaminated soil [124]. For example, chemical oxidants like potassium permanganate or hydrogen peroxide can be used to break down organic pollutants, including 2,4-D [124]. This method offers rapid treatment and can be highly effective in specific cases, especially when contamination is limited to the surface or localized areas. However, chemical remediation is often associated with significant drawbacks. The application of chemical agents may introduce secondary pollutants into the environment, which can lead to further contamination. Additionally, chemical reactions between the introduced chemicals and the contaminants, or other substances present in the soil, may produce more harmful by-products [125]. Moreover, the effectiveness of chemical remediation is highly dependent on the nature and concentration of the contaminants, as well as the soil's chemical properties. In some cases, residual chemicals may remain in the soil, further complicating the environmental impact [126].

Thermal techniques, such as soil incineration and soil vapor extraction, are employed to treat organic contaminants, including 2,4-D, by applying heat (300–600 °C) to volatilize and decompose pollutants into less harmful substances, such as CO_2 and water H_2O [127]. These methods are highly effective for removing volatile organic compounds and can treat a broad range of organic pollutants. However, thermal techniques come with notable drawbacks. They are costly due to the energy-intensive nature of the heating process and require careful management of volatile organic compounds (VOCs) released during treatment [127]. Furthermore, these methods can cause significant damage to soil structure, leading to a loss of soil fertility and microbial diversity. The high temperatures required for effective treatment can also lead to the destruction of soil microorganisms, which are essential for maintaining soil health and ecosystem services. Moreover, the thermal treatment process may not be suitable for deep or widespread contamination, as it typically targets only the surface layers of the soil [128]. Recent studies have also demonstrated the efficacy of clay@MOF composites in removing 2,4-D from aqueous environments, showing enhanced adsorptivity, reduced phytotoxicity, and resilience against interference from co-existing ions [129]. Biochar and nanocomposite adsorption are showing a promising potential in remediating contaminated soil, including 2,4-D contaminated soil, as depicted in Table 1.

9 Challenges and limitations in field applications

The application of BC/g-C_3N_4 nanocomposites for the remediation of organic pollutants, such as 2,4-D, and for amending infertile soils, presents numerous advantages, including operational simplicity, high efficiency, and accessibility of materials. BC, derived from biomass, is a readily available and relatively cost-effective material, while g-C_3N_4 provides

Table 1 Comparison of 2,4-D remediation efficiency in soil using various treatment methods

Treatment methods	2,4-D removal efficiency (%)	Temperature (°C)	Treatment duration (days)	Initial 2,4-D concentration (mg/Kg)	Soil pH	Reference
Wind-powered driven electro remediation	53.9	25	15	1	8	[130]
Electrochemical-assisted soil washing	75.2	20	0.25	20	7.5	[131]
Sorption using clay soil	55.0	25	60	1,800	5.8	[132]
Degradation using Acinetobacter Sp. ZXO2	99.0	20	4	200	6	[133]
Bioremediation using bio-slurry	92.0	25	14	500	8.2	[134]
Maize straw biochar/Fe^{o} nanocomposite	53.2	20	3	10,000	6.2	[135]
Bioremediation using Burkhoderia Cepacia Sp	67.0	30	10	50	7.1	[136]
Electro bioremediation	99.0	28	10	20	8	[137]
Bioremediation using Cupriavidus necator Sp. JMP134	94.0	28	15	500	6.5	[138]

Note While Table 1 highlights a range of treatment methods for 2,4-D remediation, including biochar-based nanocomposites (e.g., maize straw biochar/FeO), there is currently limited direct evidence in the literature for the application of biochar/g-C_3N_4 nanocomposites specifically in 2,4-D degradation. This gap underscores the novelty and relevance of exploring such composites in future studies unique photocatalytic properties that aid in the degradation of organic pollutants [44, 139]. However, despite these benefits, several limitations hinder the widespread adoption of this technology at a large scale. One significant challenge is the dependence on light sources for photodegradation, as the process primarily requires UV radiation to activate the nanocomposite [140]. This limitation necessitates the use of artificial UV light during nighttime applications or in regions with insufficient sunlight, leading to increased operational costs.

Recent advances have focused on overcoming this UV-dependence by modifying g-C_3N_4 through element doping (e.g., with oxygen, sulfur, or metals like Fe and Co) and heterojunction formation with other semiconductors to extend its activity into the visible light range [141–144]. These strategies have shown enhanced photocatalytic performance under natural sunlight, potentially reducing energy costs and improving field applicability. Furthermore, the scalability of BC production is constrained by the need for size reduction and carbonization, both of which can be energy-intensive and costly, thus increasing the overall expense of large-scale applications [145, 146].

While g-C_3N_4 is chemically stable and relatively non-toxic compared to other nanoparticles, its environmental risks in field applications must be carefully considered [147]. The potential for leaching of nanoscale materials into the environment, coupled with their long-term behavior in soil ecosystems, remains a key concern [148]. While g-C_3N_4 exhibits low toxicity in laboratory settings, its behavior under real-world conditions, such as soil pH variations, microbial interactions, and potential bioaccumulation in plants, requires further investigation to fully understand its environmental implications. For instance, studies have shown that g-C_3N_4 can leach into surrounding soil and water systems, with potential ecotoxicological effects on aquatic organisms such as *Daphnia magna* and *Chlorella vulgaris* at elevated concentrations [149]. Moreover, its interaction with soil microbiota may alter microbial community structures, which could have cascading effects on nutrient cycling and soil health. For instance, Yan et al. [150] demonstrated that g-C_3N_4 significantly altered microbial community composition in cadmium-contaminated soils, affecting functional gene abundance related to C/N/P cycling. However, this potential disruption may be mitigated by incorporating biochar into the nanocomposite, as biochar has been shown to enhance microbial diversity and stabilize soil microbial networks, thereby promoting nutrient cycling and soil resilience [151].

Additionally, unlike water and wastewater treatment, where adsorbents can often be reused, the reusability of BC/g-C_3N_4 in soil is more limited due to the complex interactions with soil matrixes. In soils, these materials may lose effectiveness over time due to factors such as surface fouling, microbial degradation, and the incorporation of pollutants that can impair their adsorption or catalytic efficiency. Therefore, long-term sustainability in soil applications becomes a critical challenge, as repeated reapplication may be necessary to maintain effective pollutant degradation.

10 Future perspectives and research directions

The rapid pace of urbanization and population growth has led to an exponential increase in global food demand, necessitating an urgent need to improve both the quality and quantity of crop production [152]. A major challenge to achieving this goal is the competition between crops and pests for essential nutrients, which can significantly hinder plant growth and productivity [153]. To combat this, herbicides such as 2,4-D have been widely utilized, particularly in developing countries, due to their effectiveness and low cost. However, while 2,4-D helps control pests and boost crop yields, its widespread application leads to significant environmental contamination, particularly in soil and water, with adverse effects on both human health and ecosystems [154]. Thus, the remediation of 2,4-D from contaminated environments is essential to safeguard public health and preserve the integrity of ecosystems while maintaining agricultural productivity.

One important question that arises when using BC/g-C_3N_4 nanocomposites for 2,4-D degradation is the balance between pest control and the risk of crop productivity loss. While the removal of 2,4-D from the soil may mitigate its environmental and health impacts, it also raises concerns about how to control pests in the absence of this herbicide. The BC/g-C_3N_4 nanocomposite, however, is not intended to replace 2,4-D for pest control but to serve as a tool for degrading 2,4-D and improving soil health by removing harmful chemical residues. This remediation of contaminated soil is crucial for restoring soil microbial communities, enhancing plant growth, and fostering a cleaner, healthier environment, which in turn supports more effective pest management strategies. To address concerns about pest control in the absence of 2,4-D, future research could focus on integrating biological control agents, plant resistance breeding, or the use of pest-repelling plants within an Integrated Pest Management (IPM) framework [155, 156]. By combining biochar-based nanocomposites with these sustainable pest control techniques, we can develop a more holistic approach that minimizes the negative impacts of pesticide use, improves soil quality, and maintains crop productivity. Importantly, the BC/g-C_3N_4 nanocomposite contributes to this integrated system by ensuring that the soil remains free from toxic residues and supports pest resilience through improved plant health. This balance of pest management, soil remediation, and environmental protection is crucial for achieving sustainable agricultural practices and healthier ecosystems.

The integration of biochar and g-C_3N_4 nanoparticles presents a promising solution for remediating 2,4-D contaminated soil due to the high efficiency of both materials in pollutant degradation and their synergistic effects in enhancing soil fertility. The combination of biochar's large surface area, porosity, and ability to adsorb organic pollutants, with g-C_3N_4's photocatalytic degradation capabilities, can offer a highly effective approach for removing 2,4-D from agricultural environments [157–159]. However, despite its potential, the application of this nanocomposite for soil remediation requires further investigation, particularly with regard to its long-term stability, efficiency under real-world conditions, and cost-effectiveness at a large scale. Future research should explore the integration of BC/g-C_3N_4 with other technologies, such as bioremediation, phytoremediation, or solar-driven photocatalysis, to enhance the overall effectiveness of 2,4-D degradation while minimizing any unintended negative consequences. In particular, investigating the degradation pathway of 2,4-D during photocatalysis is essential to identify the transformation products formed and assess their environmental and toxicological impacts. Understanding whether these by-products pose greater risks than the parent compound will help ensure that remediation efforts do not inadvertently introduce new hazards. This line of inquiry is critical for validating the safety and sustainability of photodegradation-based treatments. Additionally, understanding the eco-toxicity and soil–plant-nanocomposite interactions over extended periods is essential to ensure that the benefits of these treatments outweigh any potential environmental risks. Therefore, future studies should focus on developing multi-faceted remediation strategies that combine technological innovations with sustainable agricultural practices, paving the way for a more resilient and environmentally friendly agricultural future.

11 Conclusion

This review underscores the synergistic potential of biochar/g-C_3N_4 nanocomposites in enhancing the photocatalytic degradation of 2,4-dichlorophenoxyacetic acid (2,4-D), a persistent herbicide of global concern. The integration of biochar not only improves the dispersion and charge separation efficiency of g-C_3N_4 but also contributes to increased adsorption capacity and microbial support, resulting in more effective and ecologically balanced remediation. This dual functionality positions the composite as a promising candidate for soil detoxification.

Despite these advantages, several challenges must be addressed before field-scale deployment, including UV-light dependence, synthesis cost, and long-term material stability. Future research should focus on tailoring the physicochemical properties of the composite to enhance visible-light responsiveness, reduce production costs, and improve durability. Additionally, evaluating the ecological interactions of these materials with soil microbiota and plant systems will be critical to ensure environmental safety. By centering on the unique synergy between biochar and g-C_3N_4, this review provides a focused framework for advancing targeted pesticide remediation strategies that are both effective and environmentally compatible.

Acknowledgements We would like to thank Addis Ababa Science and Technology University for its support.

Authors contribution S.T.G., A.W., and T.G.W. contributed to Writing—Review and Editing, Writing—Original Draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, and Conceptualization. All listed authors made significant contributions.

Funding The author(s) received no specific funding for this work.

Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interest The authors declare no competing interests.

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