

Carbon Sequestration: Dual Benefit in Climate Action and Plant Disease Management

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Abstract: Global food security has been suffering from the emerging climate crisis caused by rising atmospheric CO₂. Carbon sequestration is an implicit climate mitigation strategy. Its potential to develop plant disease resistance remains under several experiments. This review gathers evidence on these dual benefits, investigating the direct and indirect effect of carbon sequestration on environment and plant immunity. A robust review of Web of Science, Scopus, PubMed, and CAB Abstracts (2000-2024) was conducted. The findings found two key mechanisms. Firstly, elevated CO₂ (eCO₂) directly guides plant defenses by enhancing carbon fixation, thereby the carbon enters photosynthesis to accumulate the sugar which alters redox balance and stimulates salicylic acid (SA) signaling while suppressing jasmonic acid (JA). Pathogens exhibit resistance due to this shift in hormonal balance. The infestation of tomato Yellow Leaf Curl Virus (TYLCV), mainly transmitted by whiteflies, was reduced by up to 14.6% and severity by 20.0%. Secondly, proper sequestration practices based on soil passively manage disease occurrence through enhancing soil organic matter and providing compatible habitat for beneficial microorganisms. This review showed that carbon sequestration is a synergistic, climate-smart strategy. Moreover, a solution to a sustainable pathway to mitigate atmospheric CO₂ and reduce overuse of chemical pesticides which fosters the climate to combat the dramatic rise of Green House Gases (GHG). More emphasis should be given in this regard by the authorities responsible.

Keywords: Carbon Sequestration; Elevated CO₂; Plant Immunity; Salicylic Acid; Jasmonic Acid; Climate-Smart Agriculture.

INTRODUCTION

Emerging Climate and Food Security crisis

Human activity has stepped into a new revolutionized era, which is widely called the Anthropocene. It is influenced by our dominant actions on earth systems. A core concern of this era is the rapid rise in atmospheric carbon dioxide (CO₂) volume. It surpassed 420 ppm after a stable period of 800,000 years stood below 300 ppm. This is the initial driver of global climate change which is leading to increased global mean temperatures, change in rainfall patterns, and a higher level of extreme weather seasons. These changes create a direct threat to global agroecosystems, affecting the food security of the world. This climate crisis is posing threats to yield. Global crop yield has declined due to the harmful effect caused by pathogens, like fungi, bacteria, viruses, and nematodes and

the damage is recorded as 10-40% annually, threatening the livelihoods and foods of millions. Alternation of pathogen habitats, overwintering survival, and host-pathogen interactions foster climate change to elevate this trouble. In consequence pathogens have become facilitated by favorable conditions for disease infestation. Chemical pesticides cause overexposure because of poor handling which may lead to development of resistant pathogen strains, hazards to beneficial organisms, including pollinators, and health issues for farmers and consumers.

Carbon Sequestration in Mitigating Climate and Ecosystem Services

Carbon sequestration is an insightful strategy to eradicate the barriers faced in managing ecosystem and biodiversity. It is done by capturing atmospheric carbon dioxide from several sources such as industry, ocean, respiration, decomposition and finally storing in biological

sinks such as plants, soils, and oceans. This involves practices that enhance the total transfer of CO₂ from the atmosphere into plant biomass and SOM. SOM acts as a major carbon sink in nature. Practices that enhance SOC are crucial for climate change mitigation strategies all over the world.

The culture of viewing carbon sequestration only as a mitigation method is changing. It has acquired worldwide fame for its role as an essential ecosystem service. This introduces the concept of "multifunctional agriculture," which means, a single practice can deliver more than one benefit. This practice sequesters carbon can also enhance biodiversity, improve water infiltration, boost soil fertility, and as emerging evidence suggests enhancing plant health. Framing carbon sequestration as a supplier of these benefits for plant disease management, transforms it from a purely environmental strategy into a major component of sustainable agricultural resilience.

Knowledge Gap: Constructing A Bridge Between Carbon and Plant Immunity

The foundation of this review rests on compelling, yet fragmented, preliminary evidence. Studies in controlled environments have demonstrated that elevated atmospheric CO₂ (eCO₂) can significantly alter the outcome of plant-pathogen interactions. For instance, research on the Tomato Yellow Leaf Curl Virus (TYLCV) has shown that eCO₂ can reduce disease incidence and severity, coinciding with measurable shifts in plant defense hormones like salicylic acid (SA) and jasmonic acid (JA). Concurrently, a separate body of literature has documented that soil-borne and foliar diseases can be managed through complex interactions with the soil microbiome and plant physiology by adopting the carbon sequestration process, which is mainly focused on soil, containing biochar application, conservation tillage, zero tillage, soil cover, crop rotation etc.

However, a critical knowledge gap persists, since there is much promising evidence. Result based research connecting carbon with plant disease management is still in distinct areas. Atmospheric CO₂ related studies are extremely detached from soil carbon practices. A significant lack of a systematic synthesis which combines these pathways is still in initial stages. Without a convincing synthesis, the full potential of carbon management as a unique plant health management strategy remains unexplored and cannot be effectively leveraged for policy and practice.

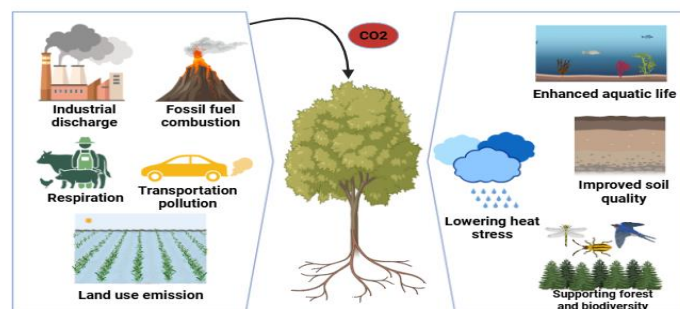


Figure 1: Major sources and environmental benefits of carbon sequestration. The left side illustrates primary anthropogenic sources of atmospheric CO₂, while the right-side highlights key ecosystem services and benefits resulting from effective carbon capture and storage (Created in <https://BioRender.com>).

Review Objectives and Research Questions

The primary objective of this systematic review is to systematically synthesize the global scientific evidence connecting carbon sequestration strategies to impactful plant disease resistance.

This review will address:

- The nature and strength of evidence that elevated atmospheric CO₂ directly influences defense pathways (e.g., SA, JA) in plants, and the mechanism of this influence's resistance against pathogens (Figure 1).
- Agroecological mechanisms' role in soil carbon sequestration practices (e.g., biochar, conservation tillage, cover cropping) and the procedure of their indirect influence on plant health.
- Integration of the direct (atmospheric) and indirect (soil/agroecological) pathways of carbon sequestration to refine climate-smart plant disease management.

MATERIALS AND METHODS

A comprehensive literature search was conducted through four major databases, such as Web of Science, Scopus, PubMed, and CAB Abstracts for recently published peer reviewed literatures between 2005 and 2025. Inclusion criteria required studies to link carbon associated management practices with plant disease control measures. Studies conducted in non-English languages as well as non-agricultural studies were excluded carefully. Once the initial screening of titles and abstracts was completed, exploration of full-text articles was done independently. Data on study design, carbon sequestration, pathogen inoculation, disease severity, and recommended strategies were extracted and synthesized into direct and indirect pathways with evidence.

THEORETICAL FRAMEWORK

This study is structured around a theoretical framework which recognizes carbon sequestration as a dual benefit for climate change mitigation as well as plant disease

management. The framework proposes two interconnected pathways through which carbon influences plant health:

The direct atmospheric pathway refers that elevated CO₂ (eCO₂) enhances photosynthetic carbon fixation, resulting in a higher leaf carbon-to-nitrogen (C:N) ratio and a metabolic reconfiguration that primes salicylic acid (SA) based defense signaling. This reprogramming strengthens plant resistance against biotrophic pathogens, such as viruses, by enabling antioxidant systems and antiviral mechanisms.

Concurrently, the indirect soil mediated pathway proposes that soil carbon sequestration practices (e.g., biochar, agroforestry, conservation tillage) enhance soil organic matter (SOM), which improves soil structure and fosters a beneficial microbiome. This, in turn, influences jasmonic acid (JA)/ethylene (ET)-mediated systemic resistance (ISR) and supports direct biological control of pathogens, suppressing soil borne and foliar fungal diseases.

The framework further integrates these pathways, acknowledging that their interaction can yield synergistic resilience or pathogen-specific trade-offs (e.g., increased susceptibility to necrotrophs under eCO₂). Moderating factors including pathogen type, crop genotype, environmental conditions, and socio-economic contexts, shape the overall outcome. This holistic model guides the review's investigation into how coordinated carbon management can underpin climate-smart agricultural systems that are resilient to both atmospheric change and pathogen pressure.

ATMOSPHERIC PATHWAYS

The direct pathway: Elevated CO₂ and the re-programming of plant defense

The most recent connection among carbon sequestration and plant defense takes place within the leaf cell under elevated atmospheric CO₂ (eCO₂). This carbon enriched environment influences a powerful physiological trigger which alters plant metabolism and defense in ways that can effectively reconstruct the response of pathogen infestation.

The Physiological Basis: From C Fixation to Metabolic Re-configuration

A terminology often known as CO₂ fertilization, when elevated CO₂ (eCO₂) generally increases the proportion of photosynthesis in C3 plants (Ainsworth & Long, 2005). This enhanced carbon fixation leads to accumulation of non-structural carbohydrates to a greater extent (sugars and starch), fundamentally re-configuring the plant's source-sink relationships and metabolic status.

A rapid change in the leaf carbon-nitrogen (C:N) ratio occurred due to a critical consequence of this shift. However, with the increase of carbon assimilation, nitrogen uptake and assimilation often do not hold the similar pace,

leading to a dilution of nitrogen-based compounds in leaf tissue (Taub et al., 2008). This nitrogenous substance is directly involved in pathogen nutrition. As a result, a higher C:N ratio can generate an optimum nutritional environment and limit pathogen success as many biotrophic pathogens feed on living host tissue and solely depend on the host's nitrogen cycle for their growth and reproduction. (Huang et al., 2019).

Molecular Crosstalk: Hormonal Signaling Under a Carbon-Rich Regime

The metabolic shifts induced by eCO₂ are intricately linked to the major hormones related to plant immunity, basically Salicylic Acid (SA) and Jasmonic Acid (JA). A robust body of evidence indicates that eCO₂ often creates a hormonal milieu that favors SA-mediated defenses for suppressing biotrophic pathogens and viruses (Figure 2).

The SA-JA Paradigm: Pathogens which require a living host for existing are oppressed by the SA pathway. In contrast, the JA pathway, often synergistically with Ethylene (ET), is crucial for defending against necrotrophic pathogens and herbivorous insects (Pieterse et al., 2012).

This antagonistic crosstalk between the SA and JA pathways grasp the molecular basis for this shift. The enhanced carbon status under eCO₂ may fuel the SA signaling cascade, which in turn JA pathways become suppressed (Thaler et al., 2012). This creates clear ecological and pathological interconnection. While tomato plants exhibit resistance to the biotrophic TYLCV under eCO₂ condition, they also become more vulnerable to necrotrophic fungi like *Botrytis cinerea* (Mhamdi & Noctor, 2016).

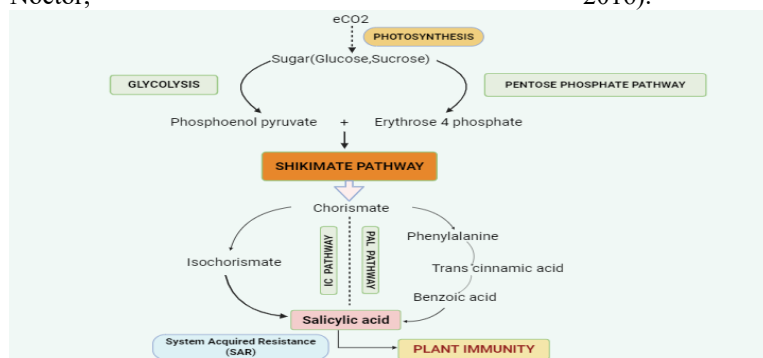


Figure 2: Shikimate pathway adjoining elevated CO₂ to Salicylic Acid based immunity (Created in <https://BioRender.com>).

Case Study: Deconstructing the TYLCV-Tomato Model

The interaction between Tomato Yellow Leaf Curl Virus (TYLCV) and tomato under eCO₂ provides a comprehensive idea about the relationship between the excessive carbon concentration and plant immunity status. Key studies by Guo et al. (2016) have been instrumental in deconstructing this relationship.

In experiments conducted under a controlled

environment, tomato plants induced to eCO₂ (750 ppm) demonstrated a 14.6 per cent reduction in TYLCV and a 20.0% reduction in disease severity in contrast to plants under ambient CO₂. The researchers interconnected this resistance to specific physiological and molecular changes:

- **Hormonal Shift:** A soar in SA levels was detected in plants under eCO₂, even before infection.
- **Redox Changes:** The plants experienced an altered redox condition, with an increase of antioxidants status, which interacts with SA signaling pathways.
- **Viral Titre:** The multiplication of viral DNA within the plant was considerably weaker under eCO₂. The primed defense system was effective at controlling viral replication and movement.

A potentiated, multi-faceted cellular defense program brings a consequential reduction in viral titre and disease severity. As synthesized in Figure 4, SA signaling is induced due to the eCO₂, altering the redox state, thus synergistic anti-viral mechanisms become activated.

As a result, RNA interference as well as a precisely regulated ROS burst have been generated to promote a hypersensitive response, and pathogenesis-related (PR) proteins expression with the aim of sectionalizing the infection. The shifts of metabolic priming under a carbon-rich regime into effective, multi-layered disease resistance at the cellular level has been epitomized via this integrated response. The plant's cellular anti-viral machinery becomes established in plant body through these systemic changes, involving a multi-layered defense program for viral components disruption and infection inhibition by accelerating RNA interference and oxidative signaling, (Figure 3)

The clear demonstration of cause and effect justifies the robustness of this model, connecting an atmospheric change to a molecular response and a tangible disease outcome. However, its generalizability must be considered with caution. The specific magnitude of resistance may vary with tomato cultivar, viral strain, and interacting environmental factors like temperature and humidity, light.

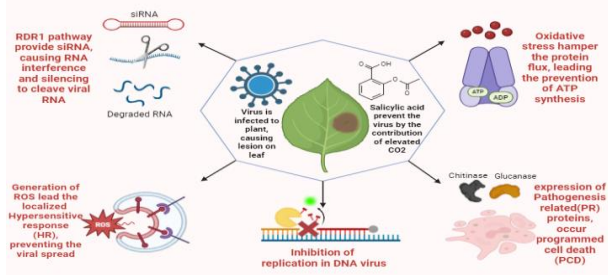


Figure 3: Cellular defense mechanisms against viral infection mediated by salicylic acid (SA) (Created in <https://BioRender.com>).

SA signaling induced by eCO₂ activates several antiviral pathways. Which combines: RNA interference (RDR1/siRNA pathway) for viral RNA degradation as well as the generation of Reactive Oxygen Species (ROS)

resulting in a localized Hypersensitive Response (HR) with restriction of viral replication. SA also plays a vital role in inhibiting the function of viral proteins and synthesis of ATP. These combined mechanisms suppress viral replication, which was observed in the TYLCV-tomato model.

The Role of Reactive Oxygen Species (ROS) and Redox Homeostasis

Reactive Oxygen Species (ROS) mainly appears as two sides of coin in plant biology which is described by the function of hydrogen peroxide (H₂O₂), causing cellular damage at high concentrations but at regulated levels it serves as crucial signaling molecules for conducting some metabolism or biosynthesis in plant body. Elevated CO₂ can lead the chloroplast holding a more reduced cellular environment, a consequence of enhanced photosynthetic electron flow (Dahal et al., 2014). This altered redox state can itself supply a signal, influencing nuclear gene expressional process known as retrograde signaling. Furthermore, eCO₂ can prime the antioxidant system, indicating a more efficient and controlled ROS burst upon pathogen infection (Mhamdi & Noctor, 2016).

This "redox priming" is a key mechanism by which eCO₂ prepares plants for defense after completion of required photosynthesis. The antioxidant system allows the plant to utilize ROS to activate defenses like. The influence of eCO₂ on ROS metabolism is not about quenching oxidative stress but about fine tuning the redox signaling network (Chao et al., 2022).

Elevated Carbon Dioxide extracted from atmosphere influences plant physiology and results in suppression of detrimental diseases (Figure 4).

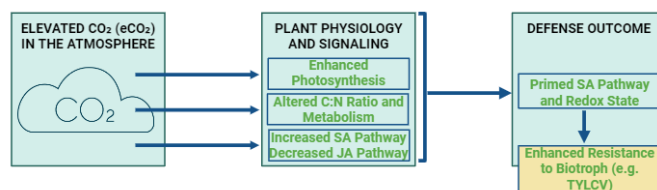


Figure 4: A model of the direct pathway where eCO₂ influences photosynthetic carbon fixation, and resistance against biotrophic pathogens (Created in <https://BioRender.com>)

The indirect pathway: Soil carbon sequestration and the creation of suppressive environments

The plant's physiology is directly controlled by elevated CO₂, while soil centric carbon sequestration methods build resilience. These sorts of practices improve soil organic matter (SOM), which is the catalyst for developing an environment that suppresses pathogens.

Biochar: A Carbon-Rich Bulwark against Disease

Biochar is produced by an exceptional technique named pyrolyzing using biomass, plant residue, organic matter to

form porous carbon-rich material that hold significant disease-suppressive qualities by providing potent soil amendment, alongside its carbon sequestration benefits.

Physical & Chemical Mechanisms: The activity of biochar becomes functional due to its high porous structure and large surface area. The physical property of biochar works as sorbent, fastening pathogenic toxins, root exudates which are harmful to plant growth as these chemicals attract pathogens. (Elad et al., 2010). As a result, the infectious pressure on plants becomes reduced through the process of detoxification" of the rhizosphere. Biochar suppresses the survival of pathogens by providing a less favorable physical environment specially for *Pythium* and *Phytophthora* spp. Through ensuring better soil aggregation, porosity, and water-holding capacity, aeration (Jaiswal et al., 2014).

Biological Mechanisms: These beneficial microbes, such as *Trichoderma* and *Pseudomonas* compete with pathogens for resources, space, light and moisture, also capable of producing antibiotics, and, crucially, induce a physiological state of resistance in the plant body known as Induced Systemic Resistance (ISR). ISR, often mediated by JA/ET signaling, primes the plant's defenses (Pieterse et al., 2014).

Evidence in Pathosystems: The effectiveness of biochar is speeded over diverse diseases. For instance, biochar amendment has been shown to minimize the severity of *Fusarium* wilt in tomato and banana by sorbing phenolic toxins and enriching *Pseudomonas* populations that are antagonistic to the pathogens (Elad et al., 2010). Similarly, *Rhizoctonia solani* root rot in common beans can be managed by this, in addition soil drainage and microbial communities that compete with the pathogen are improved (Jaiswal et al., 2014).

Agroforestry and Diversification: Ecosystem-Level Engineering for Health

Agroforestry refers to the integration of trees into cropping patterns, influences carbon sequestration and nutrient cycle that consistently manages a less conducive environment for pathogens and pests.

Microclimate Modification: The emerging complexity in agroforestry systems is a barrier to the dissemination of fungal spores. Trees can restrict the movement of wind, limiting the spread of rusts and powdery mildews. Furthermore, microclimate through reduced humidity and temperature fluctuations can check the foliar pathogens that require high humidity for their life cycle (Lin, 2011).

Increasing Functional Biodiversity: Agroforestry systems enhance the functional biodiversity by providing habitats that naturally influence pests and pathogens. This can be integrated by predators, birds, and arthropods that prey on insects which are carriers of viral diseases (Letourneau et al., 2011).

Root Exudate Diversity: Species with different root systems create a varietal soil biome. The proliferation of host-specific pathogens can be controlled through

"rhizosphere effect" by reducing the intensity of their root signals and supporting a more balanced network known as the "dilution effect" in disease ecology (Bainard et al., 2012).

Conservation Agriculture Practice

Conservation agriculture is a combination of three basic principles.

Minimum Tillage: Limited tillage reduces soil degradation, resulting in retaining the soil structure. Nutrients solubility and plant resistance to soil-borne pathogens can be confirmed via the fungal networks (Verzeaux et al., 2017).

Cover Cropping: Legumes and brassicas act as green manure in soil while incorporated as cover crops. Beyond this, brassicas like mustard and radish release glucosinolates that can break down into bioactive compounds (isothiocyanates) with strong biofumigant properties, suppressing a range of soil-borne pathogens, nematodes, and weed seeds (Larkin, 2013). Even non-biofumigant cover crops may serve as physical hurdles, lowering soil splash and breaking disease cycles by presenting themselves as non-hosts for specific pathogens during crop rotation.

These impactful practices can reduce disease infestation in major crops through varietal mechanisms (Table 1)

Table 1: A summary of major soil carbon sequestration strategies, their primary mode of action for disease control, and examples of effects on specific pathogens.

Practice	Primary Mechanisms of Suppressing Diseases	Example	References
Biochar Amendment	Absorption of toxins; better soil structure; microbiome shift towards beneficials; Induced Systemic Resistance (ISR).	Reduced disease severity in <i>Fusarium</i> wilt of tomato Suppression of <i>Rhizoctonia</i> root rot in bean.	Elad et al., 2010; Jaiswal et al., 2014
Agroforestry	Microclimate modification (↓ humidity); physical barrier to spore dispersal; enhanced functional biodiversity;	Coffee leaf rust: Reduced spread and severity. - Soil-borne diseases: General suppression via microbiome.	Lin et al., 2011; Bainard et al., 2012

	diverse root exudates.		
Conservation Tillage & Cover Cropping	Enhanced SOM and stable microbial networks; biofumigation (brassica covers); physical barrier; break disease cycles.- Take-all decline in wheat: Enhanced natural suppression.	Mustard as cover crops suppresses root-knot nematodes. .	Verzeaux et al., 2017; Larkin et al., 2013

procedures elevate fundamental soil properties, namely soil organic matter (SOM) and the beneficial soil microbiome. In return, this soil foundation generates diverse suppressive processes, namely biological control, induced systemic resistance (ISR), and enhanced physio chemical conditions, which combinedly result in effective disease control and management.

INTEGRATED DISCUSSION: A UNIFIED FRAMEWORK FOR CLIMATE-SMART PLANT HEALTH

A unified framework that positions carbon management as a central pillar of climate-smart plant health strategies can be constructed by integrating the direct and indirect pathways.

Weaving the Threads: A Holistic Carbon-Immunity Model

A model of carbon-enhanced plant defense illustrates how atmospheric and soil-based pathways create a more resilient plant system. Elevated CO₂ (eCO₂) influences increased photosynthetic carbon fixation. As a result, higher leaf C:N ratio and a rearrangement of materials that primes the Salicylic Acid (SA) defense pathway against pathogens is secured. eCO₂ introduces a cellular redox state which generates a controlled and effective defense response.

The indirect pathway exhibits soil carbon sequestration practices enhancing Soil Organic Matter (SOM). This condition supports a beneficial soil microbiome. Which induces systemic resistance (ISR) in the plant via Jasmonic Acid (JA) signaling, and results in direct biological control of pathogens.

But these pathways are not independent. They can collaborate by showcasing synergies and antagonisms. For example, the interaction between biochar and eCO₂. Biochar's ability to improve soil moisture and nutrient retention mitigate the nitrogen effect of eCO₂. For instance, plants build biomass and nitrogen-rich defense compounds as proteins and alkaloids more effectively (Lashari et al., 2013). But antagonisms must be managed at any cost. The model predicts that in an eCO₂, the suppression of JA signaling could make crops more susceptible to necrotrophic pathogens. Carbon-based management cannot be a fit for all solutions and must be modified according to the pathogen profile of a given agro-ecosystem.

Elevated CO₂ as well as soil carbon inputs influence the system of plants. The direct pathway initiates Salicylic acid dependent defense mechanisms, whereas the indirect pathway influences jasmonic acid defenses through the rhizosphere microbiome. The overall result of plant health is assessed by observing the interaction of these pathways, resulting in mitigating a broad spectrum of pathogens, though pathogen specific trade-offs (e.g., susceptibility to necrotrophs under eCO₂) must be managed (Figure 6).

Indirect Mechanisms Synthesis: A Convergent Model

Application of biochar, agroforestry, and conservation agriculture elevate Soil Organic Matter (SOM).

- Soil Environment Enhancement: Convincing water holding capacity, and availability of nutrients ensures a favorable environment for growing crops. Plants possess less susceptibility to diseases
- Activation of Induced Resistance: The reconstructed microbiome, which is rich in beneficial fungi, elevates the plant's immune system.
- Direct Biological Control: The beneficial microbes antagonize pathogens through parasitism, and antibiotic action.

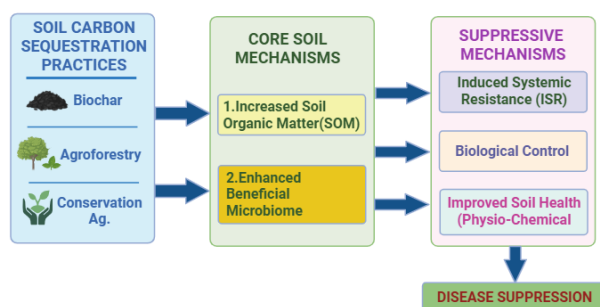


Figure 5: Convergent model depicting how soil carbon sequestration practices aiding in enhancing plant disease suppression adopting integrated soil health and microbiome-based pathways. (Created in <https://BioRender.com>)

This convergent model (Figure 5) illustrates the mechanistic connections between soil carbon management and plant health maintenance. Distinct sequestration

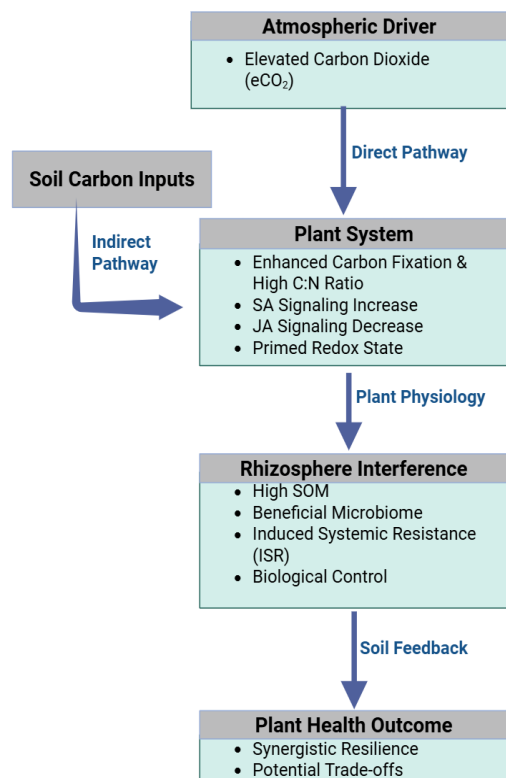


Figure 6: A holistic framework combining direct and indirect pathways of carbon mediated plant immunity. (Created in <https://BioRender.com>)

Implications for Predictive Plant Pathology and Breeding

This framework requires an evolution in how we predict disease risk and develop crop varieties. Existing disease forecast models are dependent on previous weather data and life cycle studies of pathogens. Due to rapid climate change and changing agricultural practices, these models need upgradation to incorporate C-nutrient-defense mechanisms. Future models should emphasize more on adopting real-time data on atmospheric CO₂ and soil organic carbon status to ensure more accurate predictions of disease incidence (Garrett et al., 2018).

Plant breeding must adopt new strategies. Breeding for yield has often been chosen for genotypes that perform well in input rich condition, poor SOM content for decades. The new target should be focused on varieties that can withstand high carbon conditions for both productivity and defense. This includes selecting for:

Robust Immune Priming: Genotypes that exhibit strong, primed SA and/or JA responses under the influence of both eCO₂ and beneficial microbiomes. Genotypes with robust, primed SA and/or JA responses under the control of both eCO₂ and beneficial microbiomes.

Beneficial Soil Feedback: Cultivars that withstand rhizosphere microbiomes by their root unique architecture (Wissuwa et al., 2009).

Policy, Economics, and Adoption Challenges

The primary restriction for farmers is often the short-term economic viability and risk of higher initial cost regarding shifting to practices like agroforestry or biochar application.

To overcome this situation, proper innovative policies are required. Proper subsidies and compensations must be allocated for farmers practicing these innovations for providing these public goods. This could help to alter the cost-benefit analysis, making climate-smart practices more attractive.

Solving this complex challenge requires meeting up the gaps between research organizations and educational institutions. The development of effective strategies requires thorough collaboration among scientists from different disciplines. Only these efforts can make it possible to sustain the concept of carbon immunity.

CONCLUSION & FUTURE RECOMMENDATIONS

Summary of Key Findings

This review has synthesized robust evidence establishing carbon sequestration as a strategy with a compelling dual role. We have demonstrated that beyond its critical function in climate change mitigation, carbon management directly and indirectly enhances plant immunity. Elevated atmospheric CO₂ regulate the plant defenses through a direct method, entering shikimate pathway and a shift towards SA-mediated resistance. Concurrently, the biochar application, agroforestry, and conservation agriculture are the soil carbon practices, involved as the indirect pathway to enrich soil organic matter and fostering beneficial microbiomes that induce systemic resistance in plants. These pathways reveal a complete scenario for developing a climate resilient agroecosystem.

Knowledge Gaps and Research Scopes

Despite having a bunch of evidence, critical knowledge gaps are peeping (Table 2). Future research must prioritize:

- **Sustainable Field Approaches:** Transition from controlled environments to field-based trials that simultaneously assess the effects of eCO₂, soil carbon practices, and variable climate conditions on real world disease dynamics.
- **Pathosystem Specificity:** Expanding research beyond fungal and viral models to include bacterial pathogens and plant-parasitic nematodes, whose interactions with carbon-based plant physiology are poorly understood.
- **Mechanistic Deep-Dive:** Employing advanced 'omics' technologies (e.g., metagenomics to profile soil microbiomes, transcriptomics to map defense pathways) to explore the precise molecular and ecological mechanisms considering the carbon dependent immunity link across different crop and pathogen systems.

Table 2: Identified critical knowledge gaps in understanding the carbon-plant immunity link and recommended research approaches to address them.

Knowledge Gap	Proposed Research Direction	Methodology/Tools
Interaction of Direct & Indirect Pathways	Long-term field studies assessing the combined effect of eCO ₂ and soil C practices on disease.	Free Air CO ₂ Enrichment (FACE) collaborated with soil amendment trials.
Pathosystem Specificity	Expand research into bacterial pathogens and nematodes under high C conditions.	Controlled environment and field studies focusing on host-bacteria/nematode interactions under eCO ₂ and with biochar.
Molecular Mechanisms	Detailed explanation of Carbon mediated microbiome shifts.	Integrated 'omics', such as Transcriptomics (plant defense genes), Metagenomics (soil microbiome), Metabolomics (plant & microbial metabolites).
Socio-Economic Durability	Assess the economic value of the dual benefit (C sequestration + disease reduction).	Lifecycle assessment (LCA); cost benefit analysis. Development of robust metrics for Payment for Ecosystem Services (PES) schemes.

Concluding Message

The evidence requires a visible shift in our approach to agriculture and climate. We must change our way of assessing from viewing carbon management only as a mitigation tool for atmospheric CO₂ to recognizing it as a potential, multifunctional investment in the health of our agroecosystems. By strategically managing carbon both in our skies and in our soils, we can cultivate a new era of sustainable, productive, and climate-smart agriculture that is more resilient to the intertwined challenges of pathogen pressure and environmental change. Predictive modeling also ensures science-based forecasts which assists in targeted application of treatments with minimum cost and environmental pollution (Ikram & Moni, 2025).

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Authors have used <https://BioRender.com> for generating figures.

Conflict of Interest

There are no conflicts of interest declared by the authors.

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