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Economic and Ecological Impacts of Agricultural Waste Recycling in Integrated Plant Protection Systems

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ABSTRACT

Agricultural waste recycling offers a circular approach to reducing residue burdens while supporting soil management, crop protection, and resource recovery. This review evaluates the ecological and economic impacts of incorporating compost, digestate, biochar, and related products into integrated plant protection systems. A structured narrative review of peer-reviewed literature published between 2003 and 2026 was conducted, covering disease suppression, nutrient cycling, crop productivity, greenhouse-gas emissions, life-cycle performance, and economic viability. The evidence indicates that compost provides the strongest support for suppressing soil-borne diseases through microbial competition, antibiosis, and modification of the soil environment, whereas biochar can enhance nutrient retention, regulate rhizosphere microbial communities, and induce plant resistance, although its effectiveness depends on feedstock, production conditions, and application practices. Digestate contributes primarily through nutrient recovery and renewable-energy production, with limited evidence of direct pest or disease suppression. Economic benefits include reduced fertilizer and pesticide inputs, avoided waste-disposal costs, renewable-energy generation, improved crop productivity, and potential carbon value, although these gains may be offset by processing costs, transportation, emissions, nutrient losses, and inconsistent field performance. Thus, recycled agricultural products should be regarded as complementary, context-dependent components of integrated plant protection, supported by standardized product characterization, long-term field validation, and integrated ecological and economic assessment.

INTRODUCTION

Agricultural production generates large quantities of crop residues, animal manure, agro-industrial by-products and other biodegradable materials containing recoverable nutrients, organic carbon and energy. When these materials are poorly managed, they can contribute to nutrient loss, water contamination, greenhouse-gas emissions and increasing waste-disposal costs. Conventional crop protection creates additional pressures through its dependence on synthetic pesticides, whose use is associated with production costs, environmental contamination, human-health risks and effects on non-target organisms (Pimentel, 2005). Agricultural waste recycling provides an opportunity to address these problems by converting residual biomass into fertilizers, soil amendments, biological products and renewable energy. This approach is consistent with circular agriculture, which seeks to maintain the productive value of resources while reducing waste generation and dependence on external inputs (Ghisellini *et al.,* 2016). Composting, anaerobic digestion, pyrolysis and energy recovery are among the principal technologies available for converting agricultural residues into useful products (Scarlat *et al.,* 2010; Mirabella *et al.,* 2014).

Integrated plant protection combines preventive agronomic practices, biological regulation, pest monitoring and selective pesticide application to maintain pest populations below economically damaging levels (Barzman *et al.,* 2015; Pretty & Bharucha, 2015). Within this framework, recycled agricultural materials may serve both production and protection functions. Compost, digestate, biochar and compost-derived extracts can return nutrients and organic matter to soil while modifying conditions that influence crop health and pathogen development. Organic amendments may suppress soil-borne diseases by changing nutrient availability, releasing inhibitory compounds, stimulating antagonistic microorganisms and altering the physical and chemical conditions of the root environment (Bailey & Lazarovits, 2003; Mahmud *et al.,* 2025). Anaerobic digestion also converts farm and agro-industrial wastes into biogas and nutrient-rich digestate. However, the agricultural value of digestate depends on its feedstock, nutrient composition, processing conditions, application rate and compatibility with crop demand (Möller & Müller, 2012; Nkoa, 2014).

Evidence indicates that recycled organic materials can contribute directly to disease management. Agricultural waste-based composts have suppressed Rhizoctonia solani and Sclerotinia minor, demonstrating their potential to function as both soil amendments and plant-protection inputs (Pane *et al.,* 2013). Compost-mediated suppression results from interactions among amendment

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composition, microbial competition, antibiosis, induced plant resistance and changes in the resident soil microbiome (Hadar & Papadopoulou, 2012; Bonanomi *et al.,* 2018). Biochar can also influence plant-pathogen interactions by modifying soil microbial communities, adsorbing biologically active compounds and inducing systemic resistance to soil-borne and foliar pathogens (Elad *et al.,* 2010; Jaiswal *et al.,* 2014). Nevertheless, these protective effects are not universal. Biochar performance varies with feedstock, pyrolysis temperature, application rate, soil properties, crop species and pathogen identity. Some biochars may provide little protection or increase disease severity, emphasizing the need for product-specific and pathosystem-specific evaluation (Copley *et al.,* 2015).

The economic viability of agricultural waste recycling depends on whether reductions in fertilizer, pesticide and disposal costs outweigh expenditures on collection, transport, processing, quality control and application. Integrated management can reduce pesticide use without necessarily compromising farm productivity or profitability (Lechenet *et al.,* 2017). However, the economic and climate performance of recycling systems varies with feedstock supply, production scale, transport distance, energy recovery, product value and carbon accounting (Roberts *et al.,* 2010; Campion *et al.,* 2023). This review therefore evaluates the ecological and economic impacts of agricultural waste recycling within integrated plant-protection systems. Particular attention is given to disease and pest suppression, soil and crop responses, nutrient and resource-use efficiency, environmental trade-offs, implementation costs and the conditions under which recycled products can provide viable alternatives or complements to conventional agrochemical inputs.

MATERIALS AND METHODS

A structured narrative review was conducted to synthesize evidence from agronomic, ecological, plant-pathological, and economic studies. This approach was selected because it facilitates the integration of conceptually related studies with diverse methodologies (Snyder, 2019). Literature was retrieved from PubMed, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis Online, MDPI, and individual journal websites, covering peer-reviewed publications from 2003 to July 2026. Search terms combined agricultural waste sources, recycling technologies, plant-protection functions, and ecological and economic outcomes. The search strategy is summarized in Table 1. Eligible studies examined the conversion of agricultural or biodegradable wastes into soil amendments, energy products, or biologically active materials relevant to crop production. Studies were retained when they reported at least one outcome related to pest or disease suppression, soil fertility, crop productivity, nutrient recovery, greenhouse-gas emissions, resource use, cost, profitability, or life-cycle performance. Titles and abstracts were screened before the objectives, methods and findings of potentially relevant papers were assessed. Evidence was then organized by recycling pathway, plant-protection function, ecological effect and economic implication. Because the studies differed in materials, crops, pathogens, experimental settings and assessment methods, results were synthesized narratively.

Table 1: Literature-search and screening framework

Component	Search terms or criteria
Information sources	PubMed, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis Online, MDPI and individual journal websites
Publication period	January 2003 to July 2026
Waste-source terms	“agricultural waste” OR “crop residue*” OR manure OR “agro-industrial waste” OR “food-processing waste”
Recycling terms	compost* OR “compost tea” OR digestate OR “anaerobic digestion” OR biochar OR pyrolysis OR “waste valorization”
Plant-protection terms	“integrated plant protection” OR “integrated pest management” OR “biological control” OR “soil-borne disease” OR “disease suppression” OR pathogen* OR pest*
Ecological terms	“soil fertility” OR “soil microbiome” OR “nutrient cycling” OR “greenhouse-gas emissions” OR “carbon sequestration” OR “environmental impact”
Economic terms	“economic viability” OR profitability OR cost* OR “techno-economic analysis” OR “life-cycle costing” OR “input substitution”
Combined pattern	(waste-source terms) AND (recycling terms) AND [(plant-protection terms) OR (ecological terms) OR (economic terms)]
Inclusion criteria	Peer-reviewed studies with a verifiable DOI; direct relevance to agricultural waste recycling, crop production, or plant protection; and reporting of ecological, agronomic, disease-management, or economic outcomes
Eligible study types	Primary experiments, field studies, reviews, meta-analyses, life-cycle assessments and techno-economic evaluations

Exclusion criteria	Unverifiable references; publications without a DOI; duplicate records; and studies lacking a clear connection to agricultural waste recycling or plant protection
Screening process	Title and abstract screening followed by assessment of objectives, methods and findings
Verification	DOI-title matching and confirmation of bibliographic details through publisher or bibliographic records
Synthesis categories	Recycling pathways, plant-protection function, ecological outcome, economic implication, limitations and research gaps

RESULTS AND DISCUSSION

The results and discussion from the synthesized literature explain how agricultural waste recycling contributes to integrated plant protection and sustainable agricultural production. Figure 1 presents the conceptual framework developed from the reviewed studies, illustrating the conversion of crop residues, manure, and agro-industrial wastes into value-added products through composting, anaerobic digestion, and pyrolysis. These recovered products support integrated plant protection by promoting disease suppression, induced resistance, microbial regulation, nutrient recovery, and reduced reliance on synthetic agrochemicals.

The reviewed evidence further indicates that these

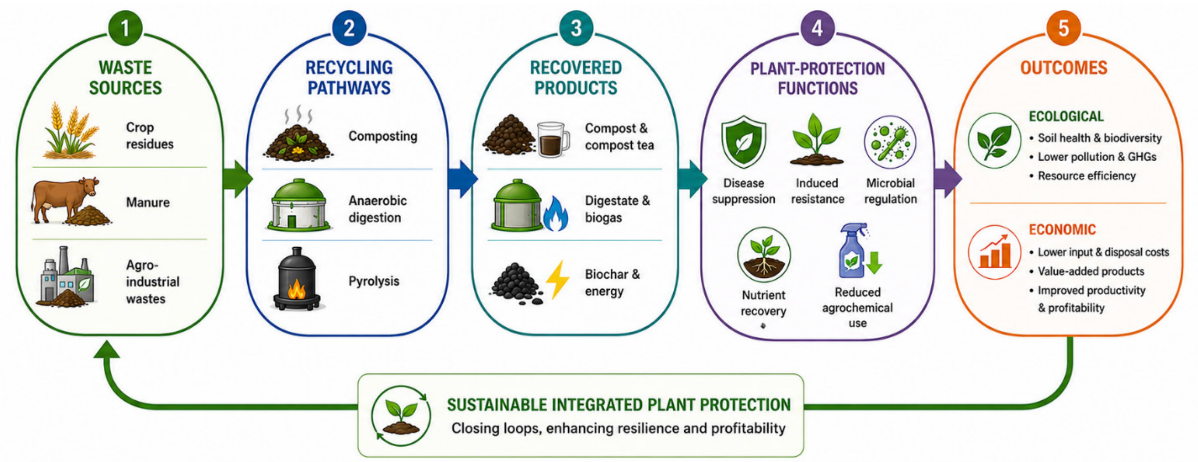

Figure 1: Conceptual framework linking agricultural waste recycling with integrated plant protection and sustainability outcomes

recycling pathways generate both ecological and economic outcomes, including improved soil health, resource-use efficiency, and farm profitability, while also involving environmental and economic trade-offs. The following sections discuss these relationships in detail according to the major recycling pathways and their ecological and economic implications.

Agricultural Waste Recycling Pathways and Their Roles in Integrated Plant Protection

Agricultural waste-derived products contribute to integrated plant protection only when they provide measurable agronomic or protective benefits. Integrated pest management combines prevention, ecological regulation, monitoring and selective pesticide use (Barzman *et al.,* 2015; Pretty & Bharucha, 2015; Jamal & Macala, 2025). Compost, digestate, biochar and compost extracts may support disease suppression, nutrient management and soil microbial regulation, but their effectiveness varies among products and production conditions (Bonanomi *et al.,* 2010; Nkoa, 2014; Jaiswal *et al.,* 2015). This section distinguishes demonstrated plant-protection effects from broader agronomic and environmental benefits.

Compost and Compost-Derived Products

Composting links organic waste management with the biological suppression of soil-borne diseases. Crop residues and organic amendments can reduce disease incidence, but their effectiveness depends on amendment properties, soil conditions and pathogen biology (Bailey & Lazarovits, 2003; Omokaro *et al.,* 2024). Compost suppressiveness is further influenced by composition, maturity, microbial activity and application rate, making it a product-specific property rather than an inherent feature of all composts (Noble & Coventry, 2005; Bonanomi *et al.,* 2010). Agricultural waste-based composts have suppressed Rhizoctonia solani and Sclerotinia minor (Pane *et al.,* 2013). However, tests of 18 composts against seven pathosystems revealed considerable variation in pathogen response (Termorshuizen *et al.,* 2006). Compost selection should therefore be based on its chemical characteristics, decomposition behavior and demonstrated efficacy within the relevant crop-soil-pathogen system (Bonanomi *et al.,* 2010). Compost-mediated suppression involves microbial competition, antibiosis, parasitism, nutrient modification and changes in the soil environment. These mechanisms arise from interactions among compost properties, beneficial microorganisms, resident soil microbiota and abiotic conditions (Hadar & Papadopoulou, 2012; Bonanomi *et al.,* 2018).

Both biological and physicochemical processes can reduce soil-borne diseases, while suppressive compost may also strengthen the natural suppressiveness of soil (Mehta *et al.,* 2014; De Corato, 2020). Compost therefore functions by modifying the soil-plant-pathogen system rather than acting solely as a direct pesticide. Microbial characterization may improve the reliability of suppressive compost. Metagenomic analysis and identification of beneficial microorganisms could support diagnostic methods for distinguishing suppressive products from inconsistent ones (Lutz *et al.,* 2020). Such methods would complement measurements of maturity, stability, salinity and nutrient content, although pathogen-specific bioassays remain necessary before field application (Termorshuizen *et al.,* 2006; Bonanomi *et al.,* 2010). Compost teas provide another means of applying biologically active compounds and microorganisms. Their contribution to sustainable tomato production has been demonstrated, but performance depends on the quality of the original compost and the chemical and microbial properties of the extract (Pane *et al.,* 2016; Lutz *et al.,* 2020). Standardized preparation, quality assessment and pathogen-specific efficacy testing are therefore required.

Anaerobic Digestion and Digestate Use

Anaerobic digestion is supported primarily as a nutrient-recovery and energy-production pathway rather than as a direct plant-protection treatment. Digestion changes the composition of organic residues and increases the proportion of nitrogen present as plant-available ammonium (Möller & Müller, 2012). Digestates possess fertilizer and amendment properties that differ from compost and digested sewage sludge (Tambone *et al.,* 2010). However, their nutrient composition and fertilizer value vary with feedstock and processing conditions (Alburquerque *et al.,* 2012). Application rates should therefore be based on chemical analysis, soil conditions and crop nutrient requirements (Alburquerque *et al.,* 2012; Nkoa, 2014). Digestate use may cause ammonia volatilization, nitrate leaching, nutrient accumulation, salinity and the introduction of undesirable constituents when storage and application are poorly managed (Nkoa, 2014). Its role in integrated plant protection should consequently be described mainly in terms of nutrient management unless suppression has been demonstrated for a specific digestate and pathosystem. Life-cycle assessments also show that biogas production alone does not determine environmental performance. Emissions occur during feedstock supply, digestion, storage and energy conversion, while results vary among production and utilization pathways (Poeschl *et al.,* 2012a, 2012b). At farm scale, outcomes also depend on the energy and nutrient systems displaced by biogas and digestate production (Van Stappen *et al.,* 2016). The overall value of anaerobic digestion therefore depends on fertilizer substitution, energy recovery, emission control, transportation, storage and the prevention of nutrient losses.

Biochar as a Soil Amendment and Disease-Management Input

Biochar properties are strongly determined by feedstock and pyrolysis conditions (Omokaro *et al.,* 2025a). It can alter the abundance, composition and activity of soil organisms, although responses vary among biochars and soils (Lehmann *et al.,* 2011). Meta-analyses report generally positive but inconsistent effects on crop productivity and nutrient cycling, confirming that biochars do not produce equivalent agronomic outcomes across soil and crop systems (Jeffery *et al.,* 2011; Biederman & Harpole, 2013). Biochar may also reduce soil nitrous oxide emissions and increase carbon persistence, but these effects depend on product characteristics, soil conditions, management and study duration (Cayuela *et al.,* 2014; Wang *et al.,* 2016). Several studies connect biochar with systemic plant resistance. Soil-applied biochar induced systemic resistance in plants and mediated strawberry responses to foliar fungal pathogens (Elad *et al.,* 2010; Meller Harel *et al.,* 2012). In tomato, biochar-induced resistance to Botrytis cinerea involved jasmonic acid signaling, while molecular responses were also associated with resistance to Fusarium crown and root rot (Mehari *et al.,* 2015; Jaiswal *et al.,* 2020).

Biochar can further influence soil-borne disease through rhizosphere modification. Suppression of R. solani in cucumber varied with feedstock, pyrolysis temperature and concentration, while disease suppression in tomato was associated with changes in belowground microbial composition and activity (Jaiswal *et al.,* 2014, 2017). Biochar has also shown potential for managing soil-borne diseases during nursery production, although its effectiveness remained product- and application-specific (Jaiswal *et al.,* 2019). Dose response is a significant constraint. Jaiswal *et al.* (2015) found a non-monotonic relationship among biochar dose, bean growth and susceptibility to R. solani, indicating that higher application rates do not necessarily improve disease control. Moreover, maple bark biochar increased damping-off severity by altering R. solani metabolism (Copley *et al.,* 2015). Biochar should therefore undergo pathogen-specific, crop-specific and dose-specific testing before being adopted as a disease-management input (Jaiswal *et al.,* 2014, 2015; Copley *et al.,* 2015).

Economic and Environmental Criteria for Pathway Selection

The viability of agricultural waste recycling depends on processing costs and the value of recovered nutrients, energy, carbon and crop benefits. Biochar performance varies with feedstock, production technology, transport, energy recovery and carbon valuation (Roberts *et al.,* 2010). A techno-economic assessment of orchard biomass also identified production scale, biomass supply, conversion costs and biochar value as major determinants of feasibility (Nematian *et al.,* 2021). More broadly, biochar profitability is context-specific and may depend on whether environmental benefits generate marketable revenue (Campion *et al.,* 2023). Life-cycle assessments reveal trade-offs beyond farm-level crop responses. The negative-emission potential of large-scale biochar production depends on processing, energy recovery, transportation and final use (Azzi *et al.,* 2019). Large-scale agricultural deployment may therefore provide soil and carbon benefits while generating burdens during feedstock collection, processing, or transport (Tisserant *et al.,* 2022). These findings demonstrate that biochar should be evaluated as a complete production and utilization system rather than solely as a soil amendment (Azzi *et al.,* 2019; Tisserant *et al.,* 2022).

Composting presents similar trade-offs. Its environmental balance includes greenhouse-gas emissions, carbon storage, fertilizer substitution and avoided organic-waste treatment (Boldrin *et al.,* 2009). Compost use in tomato production affected environmental performance through both production impacts and the substitution of conventional inputs (Martínez-Blanco *et al.,* 2009). Collection, processing and emission profiles also differ between home and centralized composting systems (Martínez-Blanco *et al.,* 2010). Consequently, composting should be evaluated across its full life cycle. For integrated plant protection, economic assessment should include pesticide and fertilizer expenditure, crop losses, yield, labor, monitoring and amendment costs. Pesticide use can be reduced without necessarily compromising productivity or profitability when preventive management is effectively implemented (Lechenet *et al.,* 2017). However, recycled amendments should only receive economic credit for pesticide substitution when their protective effects are demonstrated under field conditions. Pathway selection should therefore integrate evidence of pest or disease suppression, agronomic performance, substitution input, environmental effects and total implementation cost (Roberts *et al.,* 2010; Lechenet *et al.,* 2017; Campion *et al.,* 2023).

Ecological Impacts of Agricultural Waste Recycling in Integrated Plant Protection

Agricultural waste recycling affects nutrient cycling, soil biota, greenhouse-gas emissions, crop productivity and plant-pathogen interactions. These effects vary with feedstock, processing, application rate, soil, crop and management practices (Nkoa, 2014; Jaiswal *et al.,* 2014; Tisserant *et al.,* 2022). Ecological assessment should therefore consider both field-level outcomes and the resource use and emissions associated with production and transport (Boldrin *et al.,* 2009; Roberts *et al.,* 2010).

Soil Fertility and Nutrient Cycling

Compost recycles nutrients and stabilizes organic matter, but its environmental performance depends on fertilizer substitution, processing emissions, transport and field application. Composting can reduce reliance on waste-disposal pathways and produce useful soil amendments (Pergola *et al.,* 2018). In tomato production, compost provided benefits through fertilizer substitution and organic-matter addition, although production, transport and field emissions contributed to its life-cycle burden (Martínez-Blanco *et al.,* 2009). Greenhouse-gas assessment must therefore consider methane and nitrous oxide emissions alongside carbon storage, fertilizer replacement and avoided waste treatment (Boldrin *et al.,* 2009). Anaerobic digestion similarly recovers nutrients by increasing the proportion of nitrogen present as plant-available ammonium (Möller & Müller, 2012). Digestates possess fertilizer and amendment properties, although nutrient composition and organic-matter stability vary with feedstock and processing conditions (Tambone *et al.,* 2010; Alburquerque *et al.,* 2012).

Mineral fertilizer substitution should consequently be based on the nutrient composition of the specific digestate rather than its application volume. Excessive or poorly managed application can cause ammonia volatilization, nitrate leaching, nutrient accumulation, salinity and eutrophication (Nkoa, 2014). Storage and application practices are particularly important because ammonia and methane losses can reduce the environmental advantages of digestion (Nkoa, 2014; Poeschl *et al.,* 2012a). Biochar influences nutrient cycling mainly through carbon stabilization, nutrient retention and changes in soil biological activity. Meta-analyses report positive average effects on crop productivity and nutrient cycling, but responses differ among biochars, soils and crops (Jeffery *et al.,* 2011; Biederman & Harpole, 2013). These average responses should not be interpreted as evidence of consistent performance under all field conditions. Biochar can also alter microbial and faunal communities by modifying soil habitats and physicochemical conditions (Lehmann *et al.,* 2011). Such changes are relevant to decomposition, nutrient transformation, pathogen competition and beneficial plant-microbe associations (Lehmann *et al.,* 2011; Bonanomi *et al.,* 2018).

Soil Microbial Regulation and Disease Suppression

Compost-mediated disease suppression provides a direct ecological connection between waste recycling and plant protection. Agricultural waste-based composts suppressed R. solani and S. minor, although evaluation of 18 composts against seven pathosystems revealed substantial variation among compost-pathogen combinations (Pane *et al.,* 2013; Termorshuizen *et al.,* 2006). Suppression is associated with interactions among compost properties, resident soil communities, introduced microorganisms, pathogens, plants and abiotic conditions (Hadar & Papadopoulou, 2012; Bonanomi *et al.,* 2018). Suppressive compost may strengthen natural soil suppressiveness, but its effectiveness depends on product quality and compatibility with the receiving soil (De Corato, 2020). Organic substrates may stimulate antagonistic organisms or favor pathogen activity, depending on their decomposition products, nutrient conditions and microbial composition (Bonanomi *et al.,* 2010; Mehta *et al.,* 2014). Metagenomic characterization and identification of beneficial microorganisms could therefore improve the diagnosis and selection of suppressive composts (Lutz *et al.,* 2020).

Biochar can suppress disease through changes in rhizosphere microbial communities and plant-defense signaling. Disease suppression in biochar-amended tomato systems has been associated with changes in belowground microbial composition, diversity and activity (Jaiswal *et al.,* 2017). Biochar has also induced systemic resistance, mediated strawberry responses to foliar pathogens and activated jasmonic acid-associated resistance to Botrytis cinerea in tomato (Elad *et al.,* 2010; Meller Harel *et al.,* 2012; Mehari *et al.,* 2015). Molecular responses have further been associated with resistance to Fusarium crown and root rot (Jaiswal *et al.,* 2020). However, suppression of R. solani varies with feedstock, pyrolysis temperature and concentration, while dose responses may be non-monotonic (Jaiswal *et al.,* 2014, 2015). Maple bark biochar has also increased damping-off severity by altering R. solani metabolism (Copley *et al.,* 2015). Biochar should therefore be tested within the intended crop-pathogen system before inclusion in integrated disease management (Jaiswal *et al.,* 2014, 2017; Copley *et al.,* 2015).

Greenhouse Gas Emissions and Carbon Management

Agricultural waste recycling influences emissions through energy and fertilizer substitution, waste treatment, soil emissions and carbon storage. Biochar can support climate mitigation, but its carbon persistence depends on feedstock, soil properties and production conditions (Woolf *et al.,* 2010; Wang *et al.,* 2016). It may reduce nitrous oxide emissions, although effects vary with soil, biochar and nitrogen management (Cayuela *et al.,* 2014). Its negative-emission performance also depends on biomass supply, conversion technology, transport, energy recovery and carbon stability (Azzi *et al.,* 2019). Anaerobic digestion can substitute fossil energy and mineral fertilizer, but emissions from feedstock handling, digestion, storage and energy conversion may reduce these benefits (Poeschl *et al.,* 2012a, 2012b). Farm-scale outcomes also depend on the energy and agricultural systems displaced (Van Stappen *et al.,* 2016). Composting presents similar trade-offs because emissions must be balanced against avoided waste treatment, carbon storage and fertilizer substitution, with performance varying between household and centralized systems (Boldrin *et al.,* 2009; Martínez-Blanco *et al.,* 2010).

Ecological Trade-Offs within Integrated Plant Protection

Recycled amendments may reduce pesticide dependence and its associated effects on human health, non-target organisms and environmental quality (Pimentel, 2005). Pesticide reductions can occur without compromising productivity or profitability under effective integrated management (Lechenet *et al.,* 2017). However, substituting recycled products for pesticides or fertilizers does not automatically reduce total environmental impacts. Biochar outcomes vary with feedstock, conversion, transport, energy recovery and scale, while composting and digestion may create burdens through processing emissions, nutrient losses and transportation (Roberts *et al.,* 2010; Tisserant *et al.,* 2022; Martínez-Blanco *et al.,* 2010; Poeschl *et al.,* 2012b). Product-specific assessment is therefore essential. Compost requires evaluation of maturity, composition, microbial quality and pathogen suppressiveness (Termorshuizen *et al.,* 2006; Bonanomi *et al.,* 2010); digestate requires analysis of nutrients, stability, salinity, contaminants and emission risks (Alburquerque *et al.,* 2012; Nkoa, 2014); and biochar requires characterization of feedstock, pyrolysis conditions, dose response, carbon stability and crop-pathogen effects (Jaiswal *et al.,* 2014, 2015; Wang *et al.,* 2016). Such evaluation is consistent with integrated pest-management principles of prevention, monitoring and evidence-based intervention (Barzman *et al.,* 2015).

Economic Impacts of Agricultural Waste Recycling in Integrated Plant Protection

Agricultural waste recycling can generate value through avoided disposal, fertilizer and pesticide substitution, renewable energy, crop improvement, carbon benefits and recycled-product sales. These benefits must be weighed against collection, transport, processing, storage, testing and application costs (Roberts *et al.,* 2010; Martínez-Sánchez *et al.,* 2016; Campion *et al.,* 2023). Waste valorization is economically relevant when recovered materials replace purchased inputs or enter markets like fertilizers, energy products, soil amendments, or industrial resources (Ghisellini *et al.,* 2016; Mirabella *et al.,* 2014).

Costs and Benefits of Compost Production and Use

Composting costs include collection, transportation, processing, labor, quality testing, storage and application. These costs vary between household, farm-scale and centralized systems because of differences in transport, energy use, infrastructure and process control (Martínez-Blanco *et al.,* 2010). Economic benefits may arise from mineral-fertilizer substitution, soil restoration and avoided waste treatment (Boldrin *et al.,* 2009; Martínez-Blanco *et al.,* 2009). Composting can integrate organic-waste management with agricultural production, while organic amendments may improve soil properties and nutrient status (Pergola *et al.,* 2018; Omokaro *et al.,* 2024). However, these benefits represent profit only when yield gains and input savings exceed production and application costs. Disease-suppressive compost may reduce crop losses and chemical-treatment costs. Agricultural waste-based composts have suppressed R. solani and S. minor, while organic amendments have shown broader potential against soil-borne diseases (Pane *et al.,* 2013; Bailey & Lazarovits, 2003). However, suppressiveness varies among composts and pathosystems, creating a risk that application costs will not produce reliable disease control (Termorshuizen *et al.,* 2006). Quality testing and pathogen-specific bioassays increase costs but may reduce the risk of ineffective application (Bonanomi *et al.,* 2010; Lutz *et al.,* 2020). Bioactive compost teas have also benefited processing tomato production, although their profitability depends on preparation, labor, storage, application frequency, crop response and pesticide savings (Pane *et al.,* 2016).

Economic Implications of Anaerobic Digestion and Digestate

Anaerobic digestion produces biogas and digestates, creating potential revenue from energy and fertilizer substitution (Poeschl *et al.,* 2012a, 2012b). Digestion increases the proportion of nitrogen present as plant-available ammonium, but digestate composition varies among feedstocks and processes (Möller & Müller, 2012; Tambone *et al.,* 2010; Alburquerque *et al.,* 2012). Its fertilizer value should therefore be calculated from plant-available nutrients, transport distance, storage requirements and crop demand. Low nutrient concentration increases transport and application costs per unit of nutrient, whereas concentrated digestate produced near cropland may provide greater fertilizer savings (Alburquerque *et al.,* 2012; Nkoa, 2014). Ammonia volatilization, nitrate leaching, methane losses and inefficient energy conversion reduce both nutrient value and economic performance (Nkoa, 2014; Poeschl *et al.,* 2012a). Farm-scale results also depend on the energy and agricultural products displaced by biogas and digestate (Van Stappen *et al.,* 2016). Economic viability therefore requires coordinated management of energy production, nutrient recovery, emissions, storage and local markets. Because current evidence focuses mainly on fertilizer properties and environmental risks, digestate should not receive a pesticide-substitution value unless direct disease or pest suppression has been demonstrated (Möller & Müller, 2012; Nkoa, 2014).

Economics of Biochar Production and Application

Biochar production requires expenditure on feedstock collection, drying, preprocessing, pyrolysis, energy management, testing, transport and application. Potential revenues include biochar sales, energy co-products, waste-treatment services, crop benefits and carbon payments. Economic performance therefore varies with feedstock, conversion technology, scale, transport, energy recovery, product value and carbon accounting (Roberts *et al.,* 2010; Campion *et al.,* 2023). A techno-economic assessment of orchard biomass similarly identified residue availability, transportation, conversion costs and biochar value as major determinants of profitability (Nematian *et al.,* 2021). Biochar may create value through improved soil fertility, crop growth, climate resilience and disease suppression (Omokaro *et al.,* 2025a). However, variable crop responses make yield-based returns uncertain (Jeffery *et al.,* 2011; Biederman & Harpole, 2013). Biochar has suppressed R. solani and supported nursery disease management, but efficacy depends on feedstock, pyrolysis conditions, dose, crop and pathogen (Jaiswal *et al.,* 2014, 2015, 2019). Maple bark biochar has also increased damping-off severity, demonstrating the potential for economic losses from unsuitable products (Copley *et al.,* 2015). Carbon revenue may improve profitability, but it should be based on life-cycle emissions and verified carbon persistence because performance varies with production, transport, energy use and deployment conditions (Azzi *et al.,* 2019; Tisserant *et al.,* 2022; Wang *et al.,* 2016).

Reduced Pesticide Dependence and Avoided External Costs

Pesticide costs include direct expenditure and wider effects associated with exposure, contamination, resistance, crop losses and harm to non-target organisms (Pimentel, 2005). Integrated plant protection can reduce these costs through monitoring, preventive practices, biological control and selective pesticide use (Barzman *et al.,* 2015). Evidence from arable farms shows that pesticide reductions can be achieved without necessarily compromising productivity or profitability (Lechenet *et al.,* 2017). Biological weed control may similarly reduce herbicide use, but its economic value must include the costs of agent identification, production, release, monitoring and management (Omokaro, 2026a). Biological crop protection may be particularly relevant where farmers have limited access to purchased inputs. In Nigeria, it has been examined as a pathway linking climate adaptation, ecosystem restoration and food security (Omokaro, 2026b). However, adoption depends on access to processing equipment, biological products, technical knowledge, extension services, credit and markets. These costs must be considered when assessing the affordability of biological protection and waste recycling for smallholder farmers.

Diversification and Economic Evaluation of Agricultural Waste Value Chains

Agricultural residues can generate additional revenue through conversion into chemicals, materials, fuels and other marketable products (Mirabella *et al.,* 2014). Microalgae also provide potential pathways for carbon sequestration, bioenergy, wastewater treatment, remediation and bioplastic production (Omokaro *et al.,* 2025b). However, diversification may increase capital, processing and infrastructure costs. Economic viability therefore depends on whether revenues and environmental benefits exceed the costs of cultivation, harvesting, transport, processing and product recovery. Economic assessment should distinguish verified cash flows from estimated environmental benefits and potential returns. Farm-level analysis should include amendment costs, input savings, labor, energy, yield, crop quality and pest-related losses, while system-level analysis should consider avoided waste treatment, renewable-energy substitution, carbon storage, water-quality protection and reduced effects on non-target organisms (Pimentel, 2005; Roberts *et al.,* 2010; Martínez-Sánchez *et al.,* 2016). Future comparisons of recycled and conventional systems should account for full production costs, multi-year crop responses, market sensitivity and regional adoption constraints (Campion *et al.,* 2023; Omokaro *et al.,* 2025a; Omokaro, 2026b).

Challenges, Research Gaps and Future Directions

The principal challenge is the inconsistent performance of recycled amendments. Compost suppressiveness varies with feedstock, maturity, microbial composition, soil and pathogen and effectiveness against one disease may not extend to another (Termorshuizen *et al.,* 2006; Bonanomi *et al.,* 2010). Biochar responses likewise depend on feedstock, pyrolysis temperature, application rate, crop and pathogen. It has suppressed R. solani under some conditions but increased damping-off under others (Jaiswal *et al.,* 2014, 2015; Copley *et al.,* 2015). Standardized criteria are therefore required for compost maturity, microbial quality, biochar composition, carbon stability and pathogen-specific efficacy (Lutz *et al.,* 2020; Wang *et al.,* 2016; Omokaro *et al.,* 2025a). Much of the current evidence originates from laboratory, greenhouse, or short-term studies. Multi-season and multi-location field experiments are needed to determine whether disease suppression, nutrient retention, crop responses and carbon benefits persist under practical farming conditions (Jeffery *et al.,* 2011; Biederman & Harpole, 2013). Economic evidence is also limited. Although biochar profitability depends on production scale, feedstock supply, transport, energy recovery and product value, few studies quantify pesticide savings, avoided crop losses, or long-term yield stability (Roberts *et al.,* 2010; Nematian *et al.,* 2021; Campion *et al.,* 2023).

Evidence connecting digestate with direct pests or disease suppression remains particularly weak. Existing studies focus mainly on nutrient availability, fertilizer value, crop growth and environmental risks (Möller & Müller, 2012; Tambone *et al.,* 2010; Alburquerque *et al.,* 2012; Nkoa, 2014). Digestate should therefore be considered primarily a nutrient-recovery product until pathogen-specific effects are demonstrated. Research is also limited in developing-country and smallholder systems, where adoption depends on labor, infrastructure, technical knowledge, financing and access to suitable residues (Pretty & Bharucha, 2015; Omokaro, 2026b). Future studies should integrate field efficacy, product quality, life-cycle performance and farm-level economics. A biologically effective amendment may remain impractical if processing and application costs are high, while a profitable system may generate emissions or nutrient losses. Combining life-cycle assessment with economic analysis and field validation would identify recycling pathways that are environmentally responsible, technically reliable and financially viable (Martínez-Sánchez *et al.,* 2016; Tisserant *et al.,* 2022).

CONCLUSION

Agricultural waste recycling can strengthen integrated plant protection by converting crop residues, manure and processing waste into compost, digestate, biochar, energy and other useful products. Compost provides the clearest evidence of direct soil-borne disease suppression, while biochar can modify rhizosphere communities and induce plant resistance. Digestate contributes mainly through nutrient recovery and renewable-energy production rather than demonstrated pest or disease control. The performance of these products is highly dependent on feedstock, processing conditions, application rate, soil properties, crop species and pathogen identity. Their ecological benefits may include improved nutrient cycling, organic-matter management, carbon storage and reduced dependence on conventional fertilizers and pesticides. However, processing emissions, transport requirements, nutrient losses, variable field performance and implementation costs may reduce these advantages. Recycled agricultural products should therefore complement established plant-protection practices rather than serve as universal replacements for agrochemical inputs. Effective adoption requires standardized product characterization, pathogen-specific testing, long-term field validation and combined ecological and economic assessment. Under these conditions, agricultural waste recycling can contribute to resource-efficient crop production, environmental protection and farm profitability.

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