PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.9798

eISSN 2348-1900

REVIEW ARTICLE

Reimagining conservation agriculture: The critical role of crop residue in soil health

N Nowmika [1], M Baskar [1*], T Sherene Jenita Rajammal [1], S Rathika [1], M Selvamurugan [2], P K Karthikeyan[3] & R L Meena[4]

[1]Department of Soil Science and Agricultural Chemistry, Anbil Dharmalingam Agricultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 003, India

[2]Department of Natural Resource Management, Horticultural College and Research Institute, Tiruchirappalli District, Tamil Nadu Agricultural University, Coimbatore 641 003, India

[3]Department of Agroforestry, Forest College and Research Institute, Mettupalayam, Tamil Nadu Agricultural University, Coimbatore 641 003, India

[4]Department of Agronomy, Indian Council of Agricultural Research - Central Soil Salinity Research Institute, Karnal 132 001, Haryana, India

*Correspondence email - mbaskaruma@gmail.com

Received: 03 June 2025; Accepted: 30 July 2025; Available online: Version 1.0: 11 September 2025

Cite this article: Nowmika N, Baskar M, Sherene JRT, Rathika S, Selvamurugan M, Karthikeyan PK, Meena RL. Reimagining conservation agriculture: The critical role of crop residue in soil health. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.9798

Abstract

Developing and distributing crop production technologies that promote sustainable crop intensification is crucial for ensuring food and nutritional security for the growing global population. This challenge remains one of the most pressing issues for governments in the twenty-first century. According to the Ministry of New and Renewable Energy, India produces approximately 500 million tons of crop waste annually. Conservation agriculture offers a promising solution to manage crop residues by maintaining a permanent soil cover through mulching and incorporating crop residues into the soil. Soil is fundamental to agricultural productivity and plant growth. However, the fraction of arable soil is limited and requires careful management to prevent nutrient depletion. Soil fertility depends significantly on organic matter and soil carbon content, which are key indicators of soil health. Crop residues enrich the soil with essential nutrients, improving crop yields and altering soil characteristics. They influence water infiltration, flow and runoff and help regulate soil temperature by shielding the surface from direct sunlight. Increased residue cover reduces evaporation rates, conserving soil moisture. Agricultural residues typically contain vital nutrients up to 80 % nitrogen, 25 % phosphorus, 20 % potassium and 50 % sulphur. Incorporating these residues into the soil enhances fertility, maintains health and supports sustainable agriculture, ensuring long-term productivity.

Keywords: conservation agriculture; crop residues; soil health; sustainability

Introduction

Ensuring food and nutritional security for the growing global population remains one of the most pressing challenges for governments in the 21st century. Achieving this target will be difficult given the growing amount of agricultural land used for residential, industrial and other infrastructure developments, the depletion of water supplies and the evident impacts of climate change and agricultural variability. Furthermore, because there is insufficient funding to maintain and restore soil quality for instance, by ploughing back organic the quality of cultivating land is deteriorating, which lowers productivity and makes conventional production systems unsustainable. Every year, approximately 150 million hectares of soil in India are impacted by water erosion, while an additional 18 million hectares are impacted by wind erosion (1). Thousands of tonnes of sediments are released across each year along with runoff water. This damages aquatic ecosystems by dumping nutrients and silting water bodies, in addition to causing the loss of plant nutrients and agriculturally valuable top soil. Additionally, the sustainability of existing agricultural production practices is called into question by the widespread and severe loss in soil quality in practically all producing locations (2).

As a result, crop production technologies that promote sustainable agricultural intensification must be developed and spread. India's economy is based on agriculture. In its many agro -ecological zones, a broad variety of crops are grown and the great bulk of the land is utilized for farming. Naturally, a significant amount of crop residues is generated both on and off the farm. Animal feed, soil mulching, bio-manure production, rural home thatching and fuel for household and commercial use are all made from these crop wastes. Crop wastes are therefore extremely valuable to farmers. But a lot of the residue is burned on the farm, mostly to make room for the next crop to be sown. The use of combines for crop harvesting, the expensive cost of removing agricultural residues using traditional methods and a lack of human labour have all contributed to the problem of crop waste being burned on farms. Across the nation's states, rice, wheat, cotton, maize, millet, sugarcane, jute, rapeseed-mustard and groundnut wastes are commonly burned on farms. Recycling agricultural residue into the soil provides numerous ecosystem services, which are essential for enhancing soil health and supporting overall plant growth and productivity (3). "Conservation agriculture is an approach to manage agro ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment" (4). To achieve the goal of agricultural output that is economically, ecologically and socially sustainable, conservation agriculture was developed using the integrated management of soil, water and other agricultural resources. There are three main tenets that define conservation agriculture.

1. Direct planting through the soil cover with no seedbed preparation, resulting in minimal mechanical soil disturbance.
2. Preservation of a permanent soil cover by mulching or cultivating cover crops to shield the soil surface.
3. Adapting and varying plant relationships for perennial crops and crop rotations and associations for annual crops.

In order to physically protect the soil from agents that cause soil degradation and to supply food for soil life, the soil surface is kept covered by crop leftovers, cover crops, or biomass obtained ex situ through agro-forestry practices. Conservation agriculture strongly prohibits burning or incorporating crop leftovers. Through biological nitrogen fixation and the addition of organic matter, diverse crop rotations incorporating legumes in conservation agriculture also aid in the management of pest and disease issues and enhance soil quality (5). Conservation agriculture uses integrated agro-ecosystem management (6) and crop residues to maintain soil cover, which allows for resource and energy-efficient agricultural crop production (7).

Benefits of conservation agriculture

Soil and water conservation

Excessive tillage, removal and/or burning of crop residues and fallow systems all of which are connected to conventional farming systems can be linked to soil degradation by wind and water erosion as well as a reduction in the physical, chemical and biological characteristics of the soil (8). Because conventional tillage results in reduced formation of aggregate stabilizing elements and more physical disruption, conventional farming systems have higher levels of soil degradation (9). The effects of wind, rain and sunlight accelerate the pace of soil degradation. Soil erosion potential is reduced in conservation agriculture due to higher aggregate stability compared to conventionally tilled areas (10, 11). In conservation agriculture, the presence of crop residues on the soil surface cause a significant rise in microbial activity, which in turn causes the soil to secrete compounds that bind aggregates. Conservation agriculture shields soil from the damaging impacts of rains, strong winds and solar heat because it leaves more residues on the surface than traditional tillage. Under conservation agriculture conditions, there is less runoff, which further reduces soil erosion in conservation agriculture areas (12).

Improves soil quality

In terms of natural managed ecosystem limits, soil quality is defined as "the capacity of a particular kind of soil to function, so sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation". The physical, chemical and biological characteristics of the soil are used to evaluate its quality. A stable system with high levels of biological variety and activity, internal nutrient cycling and disturbance resistance is referred to as a healthy soil (13).

The degree of stability of aggregates is a common way to convey soil structure, which is a crucial component of soil functioning and a significant consideration when assessing the sustainability of crop production systems (14). Because tillage has both direct and indirect impacts on aggregation, conventional tillage reduces aggregation (15). In contrast to conservation agriculture, which reduces soil compaction through reduced tillage operations and the growth of deep-rooted cover crops or legumes, conventional tillage, such as the long-term use of disc tillage equipment, can cause compactness in soil subsurface layers, resulting in restricted root growth, water logging and poor aeration. It has been discovered that conservation agriculture improves aeration and water retention by lowering bulk density, especially in surface layers (16).

Soil fertility is positively impacted by residue retention, which leads to increased microbial biomass and earthworm and macro-arthropod (such as termites and ants) abundance in soil under conservation agriculture. Conservation agriculture has been shown to be successful in reducing sodicity and salinity in soils (17, 18). The high organic matter contents in the surface soil layer, which are frequently observed under conservation agriculture, can increase the cation exchange capacity (CEC) of the surface layers (19). Because legumes undergo strong nitrification followed by NO_3^- leaching and increased water loss, their inclusion in crop rotations in conservation agriculture may lower the pH of alkaline soils. As, a result, soils used in conservation agriculture are typically stratified physically, chemically and biologically, with surface layers showing enhanced soil quality.

Insect-pest, disease and weed dynamics

Numerous studies from around the world have found varying outcomes regarding insect-pest dynamics following the adoption of conservation agriculture practices. According to a survey of 45 research, 43 % of the pest species declined when tillage decreased, 28 % increased and 29 % showed no discernible effect of tillage (20). Reduced tillage tends to increase the diversity of crop-damaging insect parasites and predators, but it may also increase the quantity of insect pests. Additionally, weed suppression and insect-pest cycles are broken down by crop rotations and plant associations, which are essential components of conservation agriculture (21). Therefore, in the long run, conservation agricultural fields can manage insect pests better. However, in the early years of adoption, when predators and parasites are scarce, it is probable that insect pests will become more prevalent.

Stable crop yield

The initial soil fertility level, climate, rainfall during the season, field management practices and the kind and quantity of crop residues maintained are some of the factors that affect the short-term benefits of conservation agriculture on crop output. Higher and more consistent yields are achieved in conservation agriculture fields over time because of decreased soil degradation and enhanced physical, chemical and biological properties brought about by mulching and rotating legumes (22, 23).

With barely 5 million hectares (3.52 % of the total arable area) covered by conservation agriculture, India is still far behind the rest of the globe, which has adopted conservation agriculture practices on about 11 % of the world's arable land (24). Conventional systems, in contrast to conservation agriculture, use intensive inversion tillage techniques in conjunction with crop residue burning, which speeds up Soil Organic Carbon (SOC) oxidation processes and causes a greater loss of SOC (25, 26). This leads to greenhouse gas emissions, air pollution from burning crop residue (from soot particles, black carbon and particulate matter) and nutrient loss for plants (27). India is projected to produce 500–550 million tons of crop leftovers annually, with 91-141 million tonnes of excess residue being burned (28). The goals of conventional tillage are to break up lumps for proper tilth, expose soil pathogens and pests to sunlight for control, incorporate and remove plant detritus and reverse and mix a deep layer of soil. The long-term benefits of conventional tillage in maintaining soil health are outweighed by the fact that it exposes the soil and speeds up SOC losses. Conventional tillage is intended to break lumps for better seed germination and crop establishment, reverse and mix a deep layer of soil, incorporate and destroy plant debris and expose soil pathogens and pests to sunlight for control.

Furthermore, the conventional system's intense seedbed preparation causes significant soil deterioration and nutrient losses (29). Additionally, the conventional approach requires farmers to use agricultural equipment for several tillage operations, raising their input costs. As a result, using sustainable land management techniques to reverse the processes of land degradation has garnered international interest (30, 31). In a climate setting where high temperatures accelerate the oxidation of SOC, conservation agriculture is particularly important. By enhancing nutrient availability and balances in the rhizosphere, conservation agriculture techniques may encourage the efficient and sustainable use of nutrients through reduced leaching, increased uptake efficiency (32).

However, because of the abundance of crop wastes, which can occasionally cause nutrient immobilization, managing and applying nutrients is always a difficult issue under conservation agriculture approaches. Furthermore, as conservation agriculture and crop residue retention lead to the recycling of nutrients through crop residue decomposition, knowledge of their effects on nutrient status will aid in the strategizing of nutrient management and recommendations. Conservation agriculture-based resource conserving technologies (RCTs) such as laser-assisted precision land levelling, zero/reduced tillage, direct seeding, un-puddled mechanical transplantation of rice, raised bed planting, crop diversification and direct drilling of seeds are being used across 3 million hectares in South Asia, according to recent estimates. Innovative residue management RCTs prevent straw burning, increase soil organic carbon, boost input efficiency and could lower greenhouse gas emissions (33).

A prerequisite and essential component of conservation agriculture is the use of permanent crop cover along with crop residue recycling. However, it is problematic to plant a crop while there are remnants of the previous crop around. Even with surface residues (loose and anchored up to 10 t/ha), new types of zero-till seed-cum-fertilizer drills and planters, like the happy seeder, turbo seeder and rotary-disc drill, have been designed to drill seeds directly. These devices are highly helpful in suppressing weeds, regulating soil temperature and managing crop wastes to preserve moisture and nutrients.

Crop residues

Crop residues, which are significant natural resources that can be managed to maximize various input usage efficiencies, are the materials that remain in the field after a crop is harvested. These materials include leaves, seed pods and stalks and stubble. Crop residue management is a widely recognized technique technique, crop residue management is essential to conservation agriculture and to regulating the physical, chemical and biological properties of soil. Every year, during harvest seasons, large amounts of agricultural residues are produced, including sugarcane leaves and tops, woody stalks and cereal straws. According to Jain *et al.*, these leftovers are utilized as industrial fuel, residential cooking fuel, animal feed and thatching for rural dwellings (34).

Generation of crop residues in India

According to estimates from the Indian government's Ministry of New and Renewable Energy (35), over 500 million tons of crop residues are produced annually. Based on the crops planted, cropping intensity and crop yield, there is significant variation in the production of agricultural residues and their application in various parts of the nation. Uttar Pradesh produces the most crop residues (60 Mt), followed by Punjab (51 Mt) and Maharashtra (45 MI). Cereals have the highest residues (352 Mt) among the various crops, followed by fibres (66 Mt), oilseeds (29 MUK), pulses (13 Mi) and sugarcane (12 Mi). While rice alone accounts for 34 % of crop wastes, the cereal crops; rice, wheat, maize and millets contribute 70 %. While fibre crops account for 13 % of the agricultural wastes produced from all crops, wheat comes in second with 22 %.

Cotton produces the most fibre (53 Mt) with 11 % crop residue. With a residual generation of 12 million miles, coconut minks rank second among fibre crops. The tops and leaves of sugarcane make up 12 million litters, or 2 %, of India's agricultural residues. Additionally, Uttar Pradesh produces the most crop leftovers of cereals (53 Mt), followed by West Bengal (33 Mt) and Punjab (44 Mt). While Andhra Pradesh produces the majority of the residues from fiber crops (14 Mt), Maharashtra contributes the most to the production of pulse residues (Mt). Approximately 6 Mt of wastes from oil seed crops are produced in Gujarat and Rajasthan, respectively.

Crop residue management in conservation agriculture

Balling and removing the straw

There are several beneficial uses for agricultural surplus straw, including fuel, building materials, livestock bedding, livestock feed and composting for mushroom cultivation (36). Mulching for orchards and other crops and bedding for veggies like cucumbers, melons, etc are obtained from crop residues.

Soil mulch

A technique known as "direct drilling in the surface mulched residues" leaves agricultural residues from a prior crop on the soil's surface without incorporating them in any way. Remainder surface retention aids in preventing water and wind erosion of the rich soil surface (37). The substantial amount of residues left on the surface frequently causes equipment malfunctions, which impacts the next crop's seeding. In areas where conservation tillage or no-till methods are common, farmers typically employ these techniques. In many cases, it may be best to retain part or all of the residues on the surface. It inhibits the growth of weeds (38).

The organic carbon and total nitrogen in the top 5 to 15 cm of the soil are increased by the slow decomposition of residues on the soil surface, which also prevents erosion of the top soil. When agricultural wastes were left on the soil surface instead of being burned, the soil nitrate concentration rose by 46 %, nitrogen uptake by 29 % and yield by 37 %. It keeps the temperature of the soil constant (39).

Crop residue incorporation

Crop leftovers can either be fully or partially integrated into the soil, depending on the cultivation technique. Crop output can be increased by incorporating straw (40). The most effective technique for incorporating residue is ploughing. Due to low temperatures and the short day between rice harvest and wheat sowing, it is more difficult to include rice residues before planting wheat than it is to incorporate wheat straw beforehand. Incorporating crop leftovers raises the amounts of SOM and soil nitrogen, phosphorous and potassium, in contrast to removing or burning them.

Due to the immobilization of soil nitrogen in the presence of crop residues with a wide C/N ratio, a few studies found that wheat yields were lower during the first one to three years of incorporating rice straw 30 days before wheat planting. However, in subsequent years, the incorporation of straw had no negative effect on wheat yields. On the other hand, the addition of rice straw resulted in noticeably greater wheat yields of 3.5 t ha as opposed to 2.91 t ha when the straw was removed. A significant source of organic matter that can be recycled into the soil for nutrient recycling and to enhance the physical, chemical and biological qualities of the soil are crop leftovers, which are rich in organic carbon and mineral nutrients (41).

Effects of crop residues on soil health and sustainability

Improving Soil Physical Properties

It has been demonstrated that adding leguminous crop leftovers improves the physical characteristics of the soil, including its permeability and ability to hold water. By improving the availability of nutrients for the crops' root zone, the addition of leguminous crop leftovers also boosts crop growth and production (42). Modern input-intensive agriculture frequently uses heavy machinery and farm tools such as planters, zero-tillage tools, reapers and combine harvesters. When these heavy tools are used carelessly, they compact the soil, which impairs its physical qualities such as airflow, water-holding capacity and irrigation rate.

Applying crop residues made from straw and ryegrass along with mixed litter will greatly increase the soil's porosity and water-holding capacity, which can ultimately increase the soil's productivity (43). In rice-bused cropping systems, it has been shown that applying crop residues in conjunction with conservation tillage enhances soil aggregate and carbon storage (44).

The bulk density significantly reduced to 1.36Mg/m^3 with 100 % crop residue incorporation in comparison with 50, 25 % and no crop residue treated plots as shown in Table 1. This might be likely due to decomposition products promoting aggregate formation and thus reduce bulk density. This improvement was attributed to the incorporation of crop straw, which causes the soil particles to stick together and form aggregates. Thus, the bulk density reduced and the total porosity increased (45).

Table 1. Effect of long-term crop residue incorporation on bulk density, volumetric water content, maximum water holding capacity and porosity of soil under Rice-Wheat cropping systems

Crop residue level (% of straw incorporated)	Bulk density (Mg/m^3)	Volumetric water content (cm)	Maximum water holding capacity (%)	Porosity (%)
0	1.47	3.42	34.92	44.55
25	1.43	3.58	37.77	45.93
50	1.39	3.77	40.88	47.43
100	1.36	4.01	43.55	48.79

Improving soil chemical properties

The chemical characteristics of soil, such as pH, electrical conductivity and cation exchange capacity (CEC), as well as the conversion of various primary and secondary plant nutrients, can be effectively enhanced by the sustainable management of agricultural wastes. The application of crop residue is positively correlated with the soil carbon pool (both the total and labile pool). An irrigated maize production system's total and labile carbon pool can be considerably increased (46). In a rice-maize cropping system with residue management, conservation tillage can be used to increase apparent K balance, K use efficiency and system production. By recycling up to 15 % of the soil's available K, residue absorption also helps to reduce the need for external K supplies (47). Applying cluster bean crop residue prior to sacred basil (*Ocimum sanctum* Linn.) transplanting greatly increased the SOC and soil macronutrient availability (42).

The experiment was conducted at the KVK farm of Bihar Agricultural University in a sandy clay soil and the results are presented in Table 2. The decrease in bulk density is due to the soil organic matter make soil aggregates there by increasing infiltration rate and aggregate stability. The decrease in pH, EC is due to the release of organic acids. The increase in OC, N, P and K is due to decomposition of organic matter and release of nutrients to the soil pool (48).

Increasing the microbial activity of soil

According to reports, the dynamics of soil microbial biomass is significantly impacted by the appropriate retention of crop residues. In previous studies, applying crop residue mulching increased microbial activity in the top layer of soil (49, 50). This could be because it changes the plant-soil microclimate, increases the availability of water and nutrients and regulates soil temperature. (46) found similar results and concluded that applying wheat crop residue greatly increased soil microbial biomass carbon (MBC). They also found that adding residues of leguminous crops, such as cluster beans, increased soil microbial biomass and dehydrogenase activity compared to the control (no residue) in terms of dehydrogenase activity (DHA) (42). In a wheat-soybean cropping system, residue retention under CA has also been shown to be advantageous for lowering the population of soil nematodes (51).

The experiment was carried out at farm field KVK, Bihar Agricultural University under sandy clay soil. From the Table 3 it is clearly understood that the increase in soil microbial activity

Table 2. Effect of crop residue management in Rice-Wheat system on soil physio-chemical properties

Indicators	Crop residue management practices			
	Removed	Burned	Incorporated	Incorporated + Green manuring
Bulk density (Mg/m^3)	1.57	1.59	1.48	1.46
Infiltration rate (cm/ha)	0.32	0.32	0.38	0.41
Aggregate stability (%)	9	10	14	14
pH	6.7	6.7	6.8	6.8
EC (dS/m)	0.20	0.21	0.27	0.28
OC (%)	0.40	0.38	0.58	0.62
Avail. N (Kg/ha)	175	178	205	230
Avail. P (Kg/ha)	20	18	32	34
Avail. K (Kg/ha)	190	188	264	265

Table 3. Effect of crop residue management in Rice-Wheat system on soil microbial and enzymatic activities

Indicators	Crop residue management practices			
	Removed	Burned	Incorporated	Incorporated + Green manuring
Bacteria (*10^6)	14.5	2.6	28.36	32.25
Fungi (*10^3)	58	11	105	125
Phosphatase activity (mg p-NP/g/h)	121	124	172	178
Dehydrogenase activity (mg TPF g/24h)	32	29	55	65

is due to the incorporation of crop residues and also green manuring leads to the enhancement of availability of nutrients to the microbes there by increasing their number and activity (52).

Crop residue management for soil organic matter

The labile pool of soil organic matter is considerably altered when agricultural leftovers are added to the soil (53). It has been reported that three years of continuous residue integration greatly raises the soil's light carbon percentage, which greatly contributes to the soil's overall organic carbon content (54). Depending on residue management techniques, variations in heavy-fraction carbon (>1.6 g cm^3) lead to changes in total organic carbon in long-term practices (53). Intensive farming methods contribute to the ongoing depletion of organic matter, which has a negative impact on soil quality and the global carbon balance. In comparison to cereals, the integration of residue derived from legumes guarantees massive biomass production and enhance the net uptake of soil carbon (55). Beyond 30 cm of soil depth, legume stubbles contribute 60 % more SOC and have 49 % more carbon and 133 % more nitrogen than control plots (no residue integration). However, because of the narrow C/N ratio (12–13:1) and lower lignin concentration, green manuring of legumes has little effect on soil C storage (53). This is one of the reasons why the leftovers decompose quickly. In comparison to control plots (no residue incorporation), sun hemp residue retention produced 0.92 % more SOC and 0.64 % less soil inorganic carbon (SIC) (53). If air nitrogen could have been captured and then stored in the soil, the residue would have had a low CN ratio, increasing the amount of N available for the quick conversion of the residue from a C pool to a particulate C fraction. Different meteorological and edaphic conditions, together with residue management techniques, cause this shift in soil organic C concentration to vary by region. For example, in Europe and America, it takes around one or two decades to get the soil C content to a new equilibrium with excellent residue management, while in Australia and Asia, it takes about two decades to reach the soil C level (56).

Effects of crop residues on soil erosion

Water conservation, sediment transport erosion losses and runoff are all said to be decreased by the effective use of residues (57). Mulching also aids in lowering run off, silt in runoff water and nutrient loss. Additionally, a maximum ground cover of crop residue has been shown to minimize topsoil losses by up to 30 %. The most effective choice for a cover crop is legumes since they symbiotically contribute atmospheric nitrogen, which can enhance soil health. Residue application improves water retention and reduces runoff and sediment transport. Runoff potential reduces with increasing plant density and residue mulching (58). The choice of cropping strategy has a significant impact on soil erosion and the loss of the top fertile layer of soil. Every year, monocropping with crops that allow erosion accelerated soil and water loss. According to (59), retaining soybean residue can cut soil loss by 50 % when compared to soil that doesn't retain residue. In Ethiopia's wheat-based cropping systems, conservation tillage and crop residue management have also been shown to be successful in preventing soil loss (57).

Effects of crop residues on soil nutrient status and its availability

Since the nutrients in agricultural residues are biologically bound and must be mineralized to transform into the accessible form, plants do not immediately have easy access to them after integration (60). Following incorporation, the residues are colonized by a variety of soil microorganisms, which leads to decomposition and subsequent mineralization. This process transforms the crop residues into simple monomers such as amino acids, sugars and fatty acids, which are then further assimilated physically, chemically and biologically, ultimately transforming them into organic matter (61). Furthermore, certain nutrients found in crop residues are either linked to mineralizable organic components, such protein-bound S or phosphate ester, or they are present in the soluble inorganic form, like K^+ and SO_4 (60). Plants cannot absorb all of the nutrients at once, but they may become available over the course of the crop's life or in subsequent crops because soil microorganisms temporarily immobilize the nutrients released into the soil from residues and preserve them in forms that are gradually available. This is the benefit of incorporating crop residues into the soil. This increases the efficiency of nutrient usage and stops nutrient leaching or volatilization. In previous studies, residue retention results in a notable boost in nutrient usage efficiency (62, 63).

Repeated residue decomposition greatly increases the distribution of nutrients and earlier studies found that conservation tillage, as opposed to conventional tillage, results in a higher accumulation of organic and inorganic phosphorus on the soil surface (64). By saturating P adsorption sites on soil colloids, it has been hypothesized that increased organic matter buildup in conservation practices may increase the P concentration in accessible form. In the case of N availability, a comparable resalt was also noted (65). When crop residues are left on the soil surface, there is a noticeable difference in soil nutrient losses compared to clean tillage methods. Moreover, they regulate the infiltration rate, water content and soil temperature (3). Retained residues on the soil surface limit surface nutrient losses by minimizing soil erosion (66). On the other hand, residues that decompose quickly might cause more nitrogen losses through leaching, denitrification and occasionally through weeds' strong intake of nitrogen. Removing residues from fields raises the risk of a K shortage in the soil because residues contain a high level of total K (67).

It is interesting to note that K is not found in the organic structure of plant tissues; as a result, residue degradation has no effect on K release. The K-from the residues may be washed off by irrigation or rainfall and this nutrient may be lost from the soil in a different way if there is no crop need. This illustrates how crucial it is to manage residues while taking crop needs and nutrient release timing into account. According, to (67), the quality of the crop residue particularly the amount of nitrogen, lignin and polyphenol determines the rate of decomposition and the release of nutrients. Crop residues from cereals with high C:N ratios may require additional nitrogenous fertilizer to reduce the demand for microbial N for decomposition (53).

The experiment was conducted in a farmer's field, Bangladesh. The soil type was medium low sand and sandy loam soil. In Table 4 the increase in soil organic matter can be attributed to the surface retention of crop residues of three crops over three years and the additional carbon from increased biomass production, decreased disturbance of soil organic matter and following crop rotation with species that produce different qualities of crop residue, may also have a positive effect on soil organic matter levels. The increase in N, P in the soil is due to the biomass, especially from cereal crops contains large quantities of N and P and increased soil organic matter along with zero tillage (52).

Impact of crop residues in insect-pests and weed

Crop leftovers have direct and indirect impacts on pests when included into conservation agriculture. For instance, crop residues have a direct impact on cutworm and beetle egg laying. Pest infestation would also be impacted by lower soil temperatures and higher soil moisture content beneath crop leftovers. Residues indirectly alter the density and kind of weeds, which in turn affects insects and natural enemies. In general, crop leftovers help to lessen pest load and increase the diversity of beneficial arthropods. Numerous insects, both beneficial and harmful, may be guaranteed to survive thanks to the surface leftovers. Reduced tillage methods may have higher concentrations of pest inoculums than the traditional system, especially when crops are planted in monoculture in staggered planting arrangements. Furthermore, the survival of insects in crop residues may be impacted by the decomposition of agricultural residues as well as several other factors, including climate, crop geometry, irrigation and fertilization, cultural practices and pesticides.

The breakdown of leftovers causes a chemical shift in the soil that could influence how the host responds to pests. Phytotoxic chemicals may be produced by the breakdown of plant wastes, especially in the early phases of decomposition. Reduced tillage systems, which add a significant amount of crop residues to the soil and apply additional nitrogen to speed up the decomposition of these residues, may have detrimental effects. The survival of certain insects that often grow on weeds, especially during the fallow season, is predicted to be impacted by changes in weed ecology. The zero/reduced tillage approach may change the incidence of some insects since it shortens the time that crops are left fallow.

With less tillage, termite and white grub populations typically rise (68). However, the impact of crop residues on termite-related crop damage remains debatable. Even at very high densities, white grubs do not harm the crop when there are enough crop residues. However, because it conserves moisture, organic mulching has been shown to increase cutworm damage at some locations. Additionally, agricultural residues on the soil's surface that retain moisture may attract slugs and snails, harming crops. One of the biggest obstacles to farmers adopting conservation agriculture is the rise in insect and weed issues during the "transition period." Pest outbreaks and ecological disruption can result from the careless use of

Table 4. Effect of tillage practises and residue retention levels on soil organic matter, total N and available P under Rice-Wheat-Lentil-Jute cropping systems

Tillage practices	Organic matter		Total N (t/ha)		Available P (mg/kg)	
	R_L	R_H	R_L	R_H	R_L	R_H
ZT	8.4	9.0	0.440	0.464	7.6	9.0
ST	8.4	8.9	0.442	0.447	7.5	8.5
BP	8.0	8.4	0.416	0.438	7.2	8.3
CT	8.0	8.7	0.422	0.443	6.6	7.6

insecticides under these circumstances. As a result, it is imperative that a conservation agricultural system incorporate integrated pest management, or IPM.

Crop residues improve fertility and productivity of soil

The natural ability of soil to maintain a sufficient supply of nutrients for plants is known as soil fertility and it can be ascertained by chemically analysing the soil. However, crop yield can be used to measure soil productivity, which is the combined outcome of field conditions involving soil fertility and management parameters. The physical, chemical and biological characteristics of soil that are inherently tied to the soil's organic matter stock are closely related to soil fertility. In addition to conserving natural resources and increasing productivity through proper soil and land management, residue recycling, precision technology and the supply of plant nutrients from organic sources rather than inorganic chemicals, there has been a recent focus on sustainable environmental practices, healthy food production and preserving long-term soil fertility (69).

In global agriculture, crop residue is becoming more and more important. It is regarded as a great source of organic matter that helps to improve soil C stock, water conservation, nutrient recycling and soil qualities. It also reduces the trend of residue burning and the environmental hazards that result from its retention (70). Cereals account for 74 % of the entire amount of crop residue produced. Legumes (8 %), tubers (5 %), oilseeds (3 %) and sugar crops (10 %) came next (66). Depending on the crop species and soil fertility level, crop residue contains a variety of mineral nutrients in addition to C (66). Since it is widely known that crop residues initially immobilize the available soil N due to the high C:N ratio, it is extremely challenging to predict how many nutrients will be available to the crops at the time of crop residue integration (71).

Nonetheless, over time, this method produces high-quality organic matter, improves food crop yield and increases nutrient availability for succeeding harvests (56). Legumes are regarded as high-quality residues that contribute a significant amount of soil carbon over an extended period of time, which improves the production of food crops (72).

Conclusion

With one of the most severe rates of malnutrition, India faces the difficult challenge of providing food security for the "most populous country by 2050." Crop wastes have significant economic significance as fuel, animal feed, industrial raw materials and as a prerequisite for conservation agriculture. However, initial challenges include pest dynamics, nutrient immobilization and residue handling. Strategic integration of crop rotation, reduced tillage and appropriate machinery can mitigate these issues. Wider adoption in India requires supportive policies, farmer education and infrastructure. Ultimately, crop residues must be viewed not as waste, but as a resource vital for resilient agriculture and food security.

Future scope

The Ministry of New and Renewable Energy (MNRE), Government of India, has introduced a program that supports projects utilizing biowaste from agricultural and urban sources-such as green grasses, paddy straw and residues from agro-processing industries. These projects are eligible for Central Financial Assistance (CFA) in the form of grant-in-aid and capital subsidies. The National Crop Residue Management Policy. highlights in-situ management techniques like mulching and direct integration into soils as strategies that should be encouraged in India to stop agricultural residue burning and stop environmental deterioration in croplands. Research and creative approaches to managing crop waste are constantly being promoted by the Indian Ministry of New and Renewable Energy (MNRE) and the Indian Agricultural Research Institute (IARI).

Acknowledgements

We thank the Dean ADAC&RI, Professor and Head of the Department of Soil Science and Agricultural Chemistry, Department of Soil Science and Agricultural Chemistry and Center of Excellence in Sustaining Soil Health for their cooperation and direction when necessary.

Authors' contributions

All authors have made substantial contributions to the conception, design for the work. NN and BM have contributed to drafting or revising the manuscript critically for important intellectual content. NN formulated tables, NN and KPK designed the graphical abstract. All other authors, NN, BM, SJRT, RS, KPK and SM gave final approval of the version to be published and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Compliance with ethical standards

Conflict of interest: The authors declare no conflict of interest.

Ethical issues: None

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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