



REVIEW ARTICLE

Carbon sequestration in potato for higher biomass and tuber: A comprehensive review

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Abstract

This article aims to evaluate the potential of regenerative agriculture to improve potato production results in terms of productivity, profitability, carbon (C) sequestration and reducing C footprint. The total organic carbon (TOC) content in soil is a crucial indicator of soil quality, influencing key soil functions such as productivity, climate regulation and ecosystem services and plays a central role in enhancing potato yield while contributing to C sequestration and reduction in C footprint. The key elements affecting the storage of soil organic carbon (SOC) include soil texture, moisture patterns, TOC, carbon to nitrogen ratio (C: N), biological activity, soil pH, climate, flora types and the history of land use. Carbon moves through different pools, such as atmosphere, oceans, soil microbes and oceanic life, in the forms of carbon dioxide (CO₂), carbonates and organic matter. Manuring enhanced the soil's ability to sequester C. Pulses contribute significantly to SOC on account of their ability to fix atmospheric N, their tendency to drop leaves and their greater underground biomass. The vegetation on agricultural soil and the methods of its management affect the retention of SOC. Applying manure or amendments and/or perennial cropping systems could result in a higher buildup of SOC than conventional monocropping systems. These findings highlight that integrating regenerative and climate-smart practices in potato-based systems can simultaneously enhance soil C sequestration and crop productivity, offering a sustainable pathway for farmers. Future research should focus on quantifying long-term C dynamics and evaluating economic feasibility to support large-scale adoption.

Keywords: carbon sequestration; carbon footprint; potato; soil organic carbon; *Solanum tuberosum* L.

Introduction

Potato (*Solanum tuberosum* L.) production in India reached 60.14 million tonnes (Mt) in 2023, reflecting an increase of approximately 7.07 % compared to 2022 (1). During the same period, the export value of potatoes increased substantially. By employing management practices in potato cultivation and utilising cover crops, the application rate of nitrogenous fertiliser can be lowered, leading to reduced negative environmental impacts and enhanced economic returns for farmers (2). Soil on land contains double the carbon (C) found in the atmosphere, with estimates of soil C storage ranging from 1462–1584 Pg in the top 100 cm of the soil profile (3). Addressing climate change necessitates lowering the concentration of carbon dioxide (CO₂) in the atmosphere, attainable by decreasing CO₂ emissions and enhancing C sinks (4). The overall organic C levels in soil serve as a crucial index of soil quality, influencing various soil functions, such as initial productivity, climate control and environmental services. Its depletion is among the soil threats highlighted in the soil thematic strategy (5, 6). The 4 per mille initiative, introduced by the French Agriculture Minister at the United Nations' Climate Change Conference (COP21) in Paris in 2015, seeks to enhance soil organic carbon (SOC) stocks by 0.4 % annually via improved land and soil practices in cultivated land (7). A challenge in measuring these changes is associated with the uncertainties of

sampling or analysing SOC and calculating soil bulk density, which may be further influenced in potato-based systems due to frequent soil disturbance, shallow rooting patterns and intensive tillage practices affecting spatial variability (8). Soil organic carbon levels are consistently the outcome of the stabilisation and breakdown of soil organic matter (SOM) within the soil stabilisation and decomposition processes of SOM. Over the past decade, a paradigm shift has taken place, suggesting that both the biotic and abiotic environments are more crucial for the persistence of SOM than the qualitative details present in the organic matter, such as its complexity and composition (9). In a previous study, it was assessed that 20 distinct fractionation techniques emphasise that the fractionation of SOC (specifically, SOM) is essential for comprehending the decomposition and stabilisation processes of SOM (10). Alongside agricultural land-use practices in temperate areas, the key factors influencing SOC storage include soil texture, soil moisture conditions, biological activity, C : N, overall SOC levels, soil pH, climate, flora type and the historical land use of the locations (11). To sustain or enhance the existing SOC stock, it is essential to add more organic matter, such as crop residues, cover crops and forages, or to minimise the processes that encourage mineralisation, like soil cultivation (12, 13). In general, the strength and kind/method of management practices affect the SOC reserves in cropland soils (14, 15).

This study aims to evaluate the potential of regenerative agriculture to improve potato production outcomes in terms of productivity, profitability, C sequestration and a reduced C footprint in the Andes. Tillage, cereal mulching, legume intercropping and poultry manure applications were tested based on prior studies, indicating that these practices do not reduce potato tuber yield and may even enhance production in the Andes (16, 17). Additionally, a low-cost hand-held tool for optimising fungicide use, called disks and plastic barriers, was incorporated, drawing from research highlighting their role in optimising biocide application, thereby contributing to a reduced C footprint in Andean potato systems (18–20).

Potato importance in carbon sequestration

Potato is a vital food crop that thrives in sandy-loam soil rich in organic matter. Nevertheless, continual soil disruption during potato cultivation can swiftly lead to a quick depletion of SOC (21). Potato yield, biomass production, SOC, CO₂ emissions, soil temperature and moisture dynamics are closely interconnected components influencing the overall C balance of potato-based systems. Higher biomass production contributes to greater residue return, which enhances SOC storage and improves soil health. In turn, improved SOC positively influences tuber yield through better nutrient availability and soil structure. Field-level studies indicate that practices such as spading tillage combined with manure incorporation can enhance both ecological sustainability and agronomic performance (22). However, while field-scale measurements may indicate C sequestration, life cycle-based assessments often reveal net C emissions due to inputs such as fertilisers, irrigation and energy use. Therefore, evaluating total greenhouse gas (GHG) emissions in potato-based cropping systems is essential to determine the net ecosystem C balance (NECB). Management practices, including optimised fertiliser and water use, appropriate cultivar selection, suitable tillage systems and proper sowing time, play a crucial role in balancing productivity with C dynamics. The integration of these practices with well-designed crop rotations can significantly reduce GHG emissions and improve the overall C footprint of potato cultivation (23). Substituting all or part of the nitrogen (N) in chemical fertilisers with vermicompost might be an effective nutrient management approach for increasing SOC levels in inceptisol used for potato cropping systems in semi-arid subtropical regions of India. Nonetheless, the combined application of nitrogen, phosphorus and potassium (NPK) 50 % and N-vermicompost 50 % might be advantageous since it leads to minimal yield loss and a moderate capacity for SOC storage. Soil organic carbon enrichment (47 %) and quality (81 %) were greater in the rice-potato-wheat system as compared to the maize-potato-onion system. The organic treatments, such as NPK + crop residue 100 % and N-vermicompost + crop residue 100 %, exhibited greater stability of SOC in the rice-potato-wheat system (31 and 26 %) as compared to the maize-potato-onion cropping system. The predictability of SOC stability might be effectively determined by extractable amorphous and poorly crystalline iron (Fe), aluminium (Al), silicon (Si) and SOC in both cropping systems (24). The effectiveness of various C sequestration methods depends on soil type and ecosystems. Carbon sequestration offers potential to reduce global warming and avoid negative effects of climate change; however, the application of management strategies must be customised for various ecosystems and should remain economically feasible (25). Short-term impacts of regenerative

methods enhanced SOM with varying effects on soil pH. Combining reduced tillage, mulching and organic fertilisation can improve sustainability while maintaining productivity. Sustained adoption is crucial for reinstating soil C reserves, improving sustainability and boosting agricultural resilience (26). The rise in fungal necromass C surpassed that of bacterial necromass C in a 20–40 cm layer of the identical treatment. Soil organic carbon showed a significantly positive correlation with mineral-associated organic C and C from fungal necromass, while the correlation between SOC and both microbial necromass C and fungal necromass C was stronger in the 20–40 cm layer as compared to 0–20 cm layer. In a continuous cropping system of potato under North China conditions, the N fertilisation increased organic C in soil by boosting microbial necromass C to create mineral-associated organic C. Elevating N fertilisation through the nutrient expert system could augment a balance between the upsurge and mineralisation loss of SOC, to achieve high SOC sequestration (27). Through soil C storage, conservation agriculture has proven to be able to transform a variety of soils from C sources to atmospheric C sinks (28). Natural pasture reported lower values (54.45 and 60.02 t ha⁻¹) at both depths, whereas the fodder bank showed a higher organic C content (139.85 t ha⁻¹) at 60 cm depth and the potato monoculture (63.32 t ha⁻¹) at 30 cm depth. This highlights the significance of productive systems to accumulate more C at deeper soil depth (60 cm) as compared to lower depths (30 cm), which may be related to agricultural operations on the soil surface that cause C leakage (29).

Carbon sequestration

The pool of SOC is the largest of all terrestrial pools. The recovery of SOC reserves in agricultural fields serves as a possible absorber of atmospheric CO₂. The management and improvement of SOC is crucial for sustainable farming. Crop biomass is influenced by the cropping system and soil type under various fertilisation methods. Agriculture serves as a sink and a source of GHGs. Conservation agriculture is important for sequestering SOC by enhancing soil C sinks, lowering greenhouse emissions and providing biomass feed-stocks for energy purposes. Implementing conservation agriculture through the use of crop residues, mulch and zero-till practices aids in moisture retention, minimises soil erosion and boosts organic matter concentration in soil. Capturing C in the soil-plant system via tailored management practices could aid in reducing the effects of climate change (30). Switching from conventional tillage to zero-till can capture C at a rate of $57 \pm 14 \text{ g m}^{-2} \text{ yr}^{-1}$, not including wheat (*Triticum aestivum* L.) fallow systems, where a transition from conventional tillage to zero-till might not lead to SOC buildup. Improving rotation complexity can capture C $20 \pm 12 \text{ g m}^{-2} \text{ yr}^{-1}$, without considering a shift from continuous corn (*Zea mays* L.) to corn-soybean (*Glycine max* L.), which might not lead to a meaningful increase in SOC. Carbon sequestration rates, following a transition from conventional tillage to zero-till, are likely to peak within 5–10 years, with SOC achieving a new balance in 15–20 years (31). The biological (12.78 t ha⁻¹), grain (4.85 t ha⁻¹), stover (7.93 t ha⁻¹) yield and harvest index (37.93 %) were observed maximum in treatment with crop residue, fungal consortium at 1 kg ha⁻¹, bacterial consortium at 1 kg ha⁻¹ and 100 % recommended dose of fertiliser (RDF), closely succeeded by the treatment with crop residue, bacterial consortium at 1 kg ha⁻¹ and 100 % RDF (32). Numerous studies have indicated that soil C sequestration augmented linearly with the incorporation of organic

matter (33). It was demonstrated that approximately 16.3 % of C returned to the soil could be stored (34). The C sequestration from organic C inputs (crop and animal residues) ranged from 6.3–31 %, depending on the quantity and quality of C input (35). It was found that adding 4 and 8 t/ha of corn residues to the soil resulted in C sequestration of 0.48 and 1.02 t ha⁻¹, respectively; thus, introducing additional C through residues enhanced C sequestration in the soil (36). Multiple studies have validated the beneficial impact of cover crops on SOC (37). The SOC levels rose from 11–22 % in cover crop treatments relative to control, with C sequestration values ranging from 10–20 t ha⁻¹ in cover crop plots (38). The assessment of soil management techniques for capturing atmospheric C in agricultural topsoil can be misleading, as the terms C sequestration and C storage are often used interchangeably (39). Carbon sequestration is defined as the transfer of CO₂ from the atmosphere into the soil through plants, crop residues and other organic inputs, where it is stabilised as SOC. However, SOC accumulation is not indefinite and is constrained by saturation thresholds, beyond which the rate of C storage declines. The balance between C inputs and losses determines the equilibrium level of SOC in soil systems. Moreover, intensive tillage can disrupt this balance by accelerating decomposition and increasing the risk of reversal, leading to the release of previously stored C back into the atmosphere (40). The addition of crop residues enhances microbial activity in the soil, accelerates nutrient cycling and availability and contributes to improved soil health through C sequestration. However, only a fraction of the added C is retained in the soil, typically ranging from 10–30 %, while the remaining portion is lost through microbial decomposition and released as CO₂. Regular addition of crop residues and various organic matter enhances SOM content over time, leading to improved soil health and increased crop yield (41).

Cropland management strategies

Nitrogen fertilisation

In general, the effect of N fertilisation on SOC is defined by two opposing trends. Nitrogen fertilisation promotes primary production, which increases both above and below-ground biomass, potentially enriching SOC stocks, but it can also stimulate microbial activity and accelerate the decomposition of organic matter, leading to increased C mineralisation and potential losses of SOC as CO₂ (42). Therefore, an adequate N supply could be essential for soil C sequestration (43). It was noted that mineral fertilisation typically increased particulate organic matter in soil, whereas organic matter trapped in silt and clay fractions diminished, resulting in less stable C forms (44).

Organic manure

The physical basis for this is that increased soil aggregate turnover and accelerated SOM breakdown are caused by disturbances related to intense soil tillage. The agricultural system releases CO₂ through a variety of processes, including plant respiration, crop residue and soil oxidation, the use of fossil fuels in agricultural machinery and the manufacturing of agricultural inputs like pesticides and fertilisers. The input level of N fertiliser can be reduced by implementing management strategies in farming potatoes and using cover crops. California enhances agriculture by lowering erosion, raising water infiltration, enhancing soil surface aggregates, promoting biological-tillage to lessen compaction, raising the organic matter and C content of surface soil, regulating soil temperature and controlling weed growth. Additionally, it lowers production costs, saves time, boosts output through timely planting,

while reducing pests and diseases by promoting biodiversity and lowers GHG emissions by enhancing SOC through residue retention, minimising residue burning and reducing dependence on synthetic fertilisers (45, 46).

Farmyard manure

Farmyard manure (FYM) seems to break down quickly in soil. This increased microbial activity (priming effect) could lower the SOC reserve (47).

Unlike mineral fertilisation, incorporation of manure increased the C sequestration capacity of Mediterranean soil by about 23.5 %, which may also contribute to improved farm profitability through reduced dependence on synthetic fertilisers and enhanced soil productivity. However, the economic feasibility of such practices depends on cost-benefit considerations, including the availability, transportation and application costs of organic inputs (48). An evaluation of 80 long-term experimental locations in Europe indicated that bovine FYM boosted SOC stocks by 33 %, whereas liquid slurry raised the stocks by 17 %, a figure also attained through the usage of mineral fertiliser (49). Furthermore, although increased C sequestration may offer opportunities for C credit generation, its practical feasibility remains uncertain due to limited access to C markets and lack of standardised assessment frameworks (49). The adoption of these practices may also be constrained by barriers such as higher labour requirements, limited awareness and variability in resource availability among farmers. Nonetheless, the FYM effect on SOC decreased over time and after 10 years, no increase in SOC was observed (48).

Compost application

In 2016, the application of compost raised SOC by 24 % and also enhanced permanganate oxidisable C along with soil respiration. Multiple soil attributes showed a strong correlation with compost composition, with higher quality composts (that is, more mature, higher in C, N and other accessible nutrient concentrations), yielding the most significant improvement in soil quality. In general, well-aged composts with higher C content (that is, low ash) and increased dry matter were best for improving soil quality in potato production systems in New Brunswick (50). In a comparative long-term analysis involving four types of compost, it was highlighted that for SOC storage to improve, the application of compost must adhere to a consistent pattern (51). Vermicompost, bone meal and poultry manure are rich sources of primary and trace nutrients, wherein vermicompost is beneficial to promote porosity, bulk density, aeration and water retention, while bone meal increases the calcium (Ca) availability, which promotes root length and strength (52).

Organic waste

Numerous organic waste stream producers currently incur costs for treating or disposing of these wastes, leading to a decrease in the energy content of the waste stream (53). Initiatives for the organic waste diversion approach aim to efficiently manage organic waste, replenishing nutrients in the soil to maintain its fertility and health. When handled appropriately, organic waste can yield compost that is rich in nutrients and beneficial for nearby communities (54). Those who are involved in animal and poultry farming have used manure as a source of fuel, soil amendment and plant nutrients (55). Biogas slurry, a by-product of anaerobic fermentation of biomaterials, has been widely used as a source of nutrients in agriculture, serving as an effective waste product and environmentally friendly manure (56).

Bio-slurry is a natural manure that can help in making the soil nutrients rich and the compact soil loose (57). Biogas treatment transforms bio-slurry into a manure, which contains more N than phosphate and K while promoting soil humification, subsequently reducing erosion (58). Biogas slurry, being an excellent source of nutrients, improves soil fertility, soil structure and crop production (59). The plant remnants remaining in the field after harvesting, pruning or processing are referred to as crop residue (60). In farming regions, effective residue management practices provide numerous beneficial impacts on soil health and crop remnants can be repurposed to produce biofuel (61). Under intensive cultivation systems where potato-based cropping systems are adopted, stagnant crop yield and falling soil health and environmental quality are common problems (62). Approaches to enhance sustainability are crucial in heavily managed potato systems (63).

Zero or minimum tillage

The main objective of tillage is to establish a soil environment that promotes plant development. It is the primary reason for the decrease in soil C reserves. If additional organic matter is not reintroduced into the soil as residues, compost, or by other means, SOM are oxidised when exposed to air during tillage, resulting in a decrease in the content of organic matter. Tillage disrupts the spaces created by the microbes and plant roots. The effect on underground biology remains uncertain. As the energy from raindrops dissipates, soil aggregates are more prone to disintegrate on the exposed surface remaining after tillage. Soil erosion resulting from this process obstructs soil pores, reduces water infiltration and heightens runoff. The crust on the surface dries out and hinders plant growth (64). The main reason for soil C loss is attributed to the use of disc harrows and mould-board ploughs, which disrupt soil aggregates, expose protected organic C and increase soil aeration, thereby accelerating microbial activity and the decomposition of plant residues, leading to enhanced oxidation of C and its release as CO₂. Changes in tillage practices can lead to C sequestration in agricultural soils. As stated in earlier studies, conservation tillage includes mulch tillage, reduced tillage and no-till farming (65, 66). Conservation tillage is the advancement of innovative crop production techniques that generally involve reduced tillage, applicable to both pre-plant and in-season mechanical processes, which may lead to a certain level of crop residue being retained on the soil surface (67).

Cover crop

Cover cropping refers to the use of crop plants, such as leguminous and pseudocereal crop plants, to improve and protect the soil during intervals between two traditional crops. Cover crops such as vetch (legume) and rye (cereal) have been reported to show higher C accumulation due to their high biomass production, extensive root systems and favourable residue characteristics. Previous research indicates that six cover crops for winter and summer season were cultivated on two distinct soil types, specifically (i) gravelly loam and (ii) fine sandy soil in phytotrons at three temperatures (66). Among the winter cover crops, *Vicia faba* L. had the highest C accumulation (0.597 kg/m²), while white clover (*Trifolium repens*) recorded the lowest C accumulation (0.149 kg/m²) on fine sandy soil. Sunhemp (*Crotalaria juncea* L.), a summer cover crop, accumulated the highest amount of C (0.481 kg/m²), while castor bean (*Ricinus communis*) yielded 0.102 kg/m² at 30 °C temperature on gravelly loam soil. Following a complete cycle of winter and summer cover crops, the average SOC in the gravelly loam and fine sandy soil

increased by 13.8 and 39.1 %, respectively, when compared with organic C under the same types of soil. Due to their ability to fix atmospheric N, tendency to drop leaves and greater belowground biomass, pulses significantly add more organic C to the soil (68).

Crop rotation/ cropping sequence/cropping pattern

Crop rotation involves the cultivation of different crops on the same piece of land over consecutive years. Alternating shallow and deep-rooted crops and adding leguminous crops in rotation improve the fertility and structure of the soil. A crop that depletes specific nutrients from the soil is followed by another crop that either restores nutrients to the soil or takes up a different set of nutrients in the next growing season. The level of organic waste in the soil can be increased by altering the types of crops grown. The effectiveness of crop rotation, nonetheless, differs based on the type of crop and the intervals of rotation. The main objective of crop rotation is to restore N by sowing green manure crops following cereal and other crops. The growth of deep-rooted legumes enhances C levels in lower soil layers via rhizo-deposition and deep root biomass, forming a component of organic crop rotation. Additionally, it leads to combined livestock farming and a more effective utilisation of N. Several extensive field trials were conducted to evaluate crop rotation against monocropping (68). Research indicates that following 35 years of ongoing maize farming with a legume-based rotation, the difference in C between the rotation and monoculture maize was 20 t ha⁻¹. Additionally, the SOC found beneath the tilled layer in the legume-based rotation seemed to be more biologically resilient, suggesting that the deep-rooted crops contributed to enhancing C storage at deeper levels. It was concluded that shoot residues played a lesser role in enhancing soil C stocks in no-till ferralsol compared to roots, as root-derived C is more efficiently stabilised within soil aggregates and deeper soil layers, leading to greater long-term C storage, regardless of whether the rotations involved cover or forage crops. The plant cover on agricultural lands and the way it is managed influence the storage of organic C in the soil. The entry of organic waste via crop biomass is most prevalent in the topsoil and decreases as soil depth increases (69). In farming areas, crop variety can be enhanced through temporal means (crop rotation with catch crops) and spatial methods (multiple plant species concurrently, cover crop mixtures). Employing manure or amendments and/or perennial cropping systems can potentially increase SOC accumulation as compared to traditional mono-cropping systems (50). The effect of incorporating pulses on the upland maize-based agricultural system in the inceptisols of the Indo-Gangetic plains was analysed after seven cropping cycles, concerning the modifications in the SOC pool (68, 70).

Use of bio-fertiliser

Legumes raised soil microbial biomass at a depth of 0–30 cm and leveraging the C fraction from cover crops by soil microbes is a critical method to enhance soil C levels (71). It was proposed that the microbial efficiency in utilising C from cover crops in the soil could be improved by boosting N availability through the use of legume cover crops, resulting in elevated SOC levels (72). It was found that vetch, rye and other cover crops enhanced C levels at 6–12 cm soil depth, with a more significant increase observed in the vetch treatment at 0–6 cm soil depth, indicating that higher biomass input and residue quality play a crucial role in SOC accumulation (73). The use of legumes as cover crops before corn and tomato cultivation, under both conventional and conservation agriculture, increased soil C levels by 2.03 and 1.25 g/kg at 0–15 and 15–30 cm depths,

respectively, highlighting the importance of crop type and its biomass allocation pattern, which may vary across genotypes and influence C sequestration efficiency (74). It was demonstrated that long-term tillage, along with crop residue incorporation and bio-fertilisers, enhanced C pools and improved soil sustainability, suggesting that the balance between C inputs and losses governs soil C dynamics and could be further understood using advanced modelling approaches for predicting long-term changes (75). Applying bio-fertilisers via effective microorganism 1 (EM1) inoculation resulted in a noteworthy enhancement in the accessibility of soil nutrients' concentration in leaves and the majority of growth and yield parameters in potato (76).

Biochar

Biochar-based organic amendments have long been regarded as beneficial for soil health and plant development, as it is a C-dense substances created by the thermal decomposition of organic biomass in low-oxygen environments (77, 78). Its porous structure aids in moisture retention within the soil, making it particularly beneficial in arid areas. It enhances soil structure and uniformity by increasing the amount of stable organic matter, improving soil aeration and reducing erosion. In addition, biochar contributes to long-term C sequestration due to its recalcitrant nature, which resists microbial decomposition and allows C to remain stored in the soil for extended periods (79, 80). In general, the C sequestration capacity of subsoil (> 40 cm) needs additional study. Additionally, climate change, continuous soil degradation, consumer dietary patterns and waste generation, along with socio-economic constraints faced by farmers such as limited access to information, high initial costs and challenges in maintaining long-term economic viability, act as significant barriers to the adoption of improved agricultural management practices (81). The most significant factor contributing to the reduction of the carbon footprint is an increase in yield, followed by improvements in management practices and technology. Moreover, planting methods, personal traits and plot quality had a substantial impact on the C footprint of crops (82).

Conclusion

In conclusion, it is noted that potato, although a short-duration crop, exhibits a measurable capacity for carbon (C) sequestration, mainly through the improvement of soil organic carbon (SOC) with appropriate management. Unique agricultural methods, including minimised tillage, cover cropping and effective crop residue management, are essential bases of net C balance. Future studies should concentrate on life cycle assessments that consider all sources of emissions (fertilisers, machinery and irrigation) to yield an accurate net sequestration figure. Incorporating potato into climate-smart agricultural practices provides a viable approach for mitigating climate change and ensuring food security by enhancing SOC through improved residue management, reduced tillage and efficient nutrient and water use, while maintaining stable and higher crop productivity.

Authors' contributions

All authors have contributed equally to this review article. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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