



AGRI MAGAZINE

(International E-Magazine for Agricultural Articles)

Volume: 03, Issue: 05 (May, 2026)

Available online at <http://www.agrimagazine.in>

© Agri Magazine, ISSN: 3048-8656

Soil Organic Matter: The Invisible Engine Powering Healthy, Productive Soils

*Sara Jahnawe and Santosh Korav

Department of Plant Pathology, School of Agriculture, Lovely Professional University (Phagwara) Jalandhar- 144411, Punjab, India

*Corresponding Author's email: sarajahnawe55@gmail.com

Soil organic matter (SOM) is among the most critical yet least visible components of terrestrial ecosystems, functioning as the invisible engine that powers soil fertility, biological diversity, and global carbon cycling. Comprising plant and animal detritus at various stages of decomposition, microbial cells and tissues, and microbially synthesized substances, SOM profoundly influences the physical, chemical, and biological properties of soil. This review synthesizes current knowledge on the origin, composition, fractions, and functions of SOM, with particular emphasis on its role in soil health and crop productivity. The impacts of climate change — including elevated temperatures, intensified drought, erratic precipitation, and flooding — on SOM dynamics and soil microbiome stability are critically examined. Advances in monitoring and estimation technologies, including visible-near-infrared spectroscopy (VIRS), remote sensing (optical and SAR), digital soil mapping (DSM), and machine learning algorithms such as Cubist, Random Forest, and XGBoost, are reviewed. Evidence consistently demonstrates that integrating multitemporal remote sensing data with stable environmental covariates substantially improves SOM prediction accuracy. Furthermore, proven management strategies — including conservation tillage, crop rotations, organic amendments, and microbial biofertilization — that sustain and enhance SOM pools are discussed.

Introduction

Among other natural resources, soil is one of the crucial components of terrestrial ecosystems having numerous ecological roles ranging from nutrient cycling, water regulation, habitat creation, to carbon sequestration (Xu et al., 2026). Soil organic matter (SOM) represents an active part among different soil fractions being responsible for soil fertility maintenance, carbon cycle stabilization, and providing ecosystem services (Sewpersad et al., 2024; Xu et al., 2026). However, the importance of SOM goes beyond agriculture: four to six times more carbon is stored in organic matter of the world's soil profiles than in its vegetation, rendering soils the major carbon pool of the planet (Gurmu, 2019).

SOM is the soil fraction including organic remains of plants and animals in their decomposition phases, cells and tissues of soil microorganisms, and metabolites of these microorganisms (Gurmu, 2019). Humification is the process transforming SOM into humus which is the compound of substances resistant to degradation by microorganisms. The dynamic part of soil exerts a predominant effect on numerous soil properties and functions of soils including enhanced soil aggregate formation, nutrient exchange facilitation, improved soil moisture retention, soil compaction mitigation and surface crusting reduction, and increased water penetration (Gurmu, 2019). Though low in quantity, SOM has significant implications on the functionality of the soil (Gurmu, 2019). SOM is also important in the global carbon cycle, which determines climate change and acts as both a sink and source of carbon (Sewpersad et al., 2024).

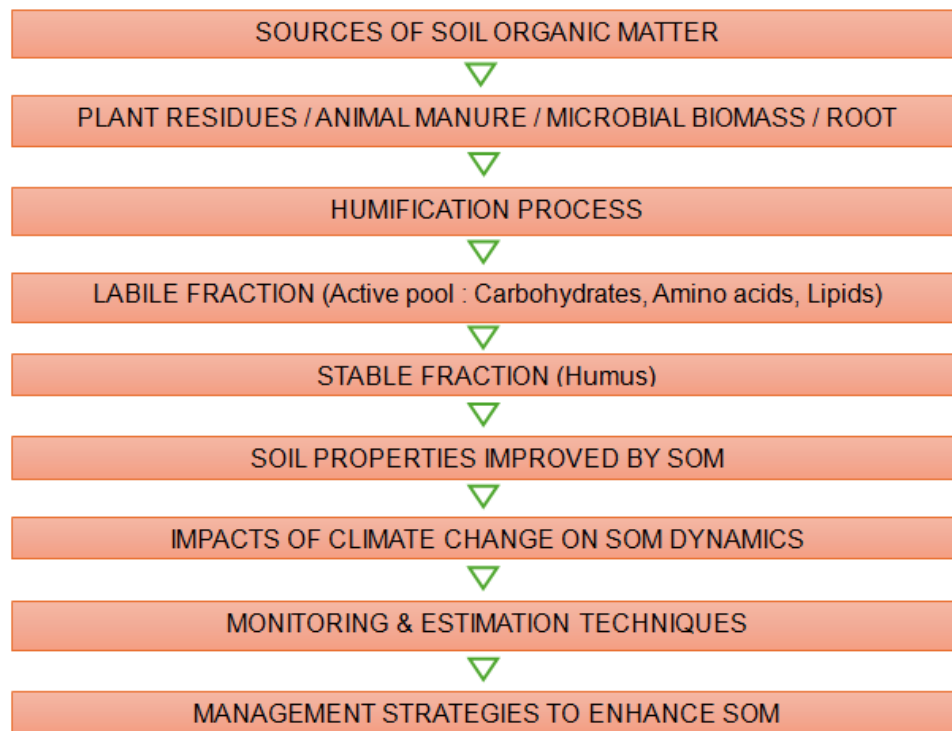


Figure: Conceptual Flowchart – Soil organic matter as the Engine of Soil health

SOM Fractions, and SOM Measurement

SOM Fractions: Labile and Stable Pools

SOM is categorized into labile and humus fractions due to the fact that whereas some of its compound molecules are easily transformed, others are safeguarded against deterioration in the soil milieu, especially when they are associated with soil mineral particles and aggregates (Gurmu, 2019). The labile OM fraction includes plant residues, macro-OM, the biomass fraction, and the non-humic OM, which is not associated with soil minerals. The most common elements of labile fractions include carbohydrates, amino acids, peptides, amino sugars, lipids, cellulose, hemicellulose, waxes, fats, resins, and lignin. Labile SOM fractions respond to changes in carbon input to the soil very readily (Gurmu, 2019).

Conventional Methods of Measurements

A number of measurement methods based on laboratory tests include the Walkley-Black test, Loss on Ignition, Automated Dry Combustion, and Humic Matter tests (Sewpersad et al., 2024). The Walkley-Black test involving potassium dichromate and sulphuric acid to calculate oxidizable carbon is among the most widely used conventional methods of SOM measurements worldwide (Sewpersad et al., 2024). However, these techniques are relatively expensive, time-consuming, and destructive, thus inappropriate for regular SOM testing in vast territories. These drawbacks have contributed to the emergence of rapid and non-destructive measurement methods such as visible-near-infrared spectroscopy (VIRS) (Dong et al., 2021).

Spectroscopic Estimation of SOM: VIRS and Machine Learning

The work by Dong et al., (2021) proved that the implementation of VIRS along with Cubist machine learning algorithm with SPA and CARS wavelength selection yielded better results than the PLSR, SVM, and ANN methods in predicting SOM. The AFS-SPA+CARS-Cubist approach attained validation R^2 scores of 0.9782, RPD score of 3.0203, and RPIQ score of 4.4164. These metrics indicate the superiority of the model in terms of its predictive capabilities (Dong et al., 2021). Similarly, (Sewpersad et al., 2024) used the combination of partial least squares regression and first-order derivative transform pre-processing to analyze the relationship between SOM and spectral reflectance for the soils in KwaZulu-Natal, South Africa. They found that there was a moderate correlation between SOM and spectral

reflectance ($r = -0.39$ at 700 nm). Agricultural lands were found to have the highest levels of SOM (2.98%), followed by eroded lands (1.56%).

Remote Sensing and DSM

Xu et al., (2026) proposed a comprehensive modeling approach which integrates the imagery during the optimal bare soil period, multi-temporal growing season data, and other environmental factors that remain constant using Cubist as the baseline model in a typical black soil area in Northeast China. According to their findings, the optimal window for obtaining the imagery varies based on the interannual climate situation, as in the year 2019 where there is drought, the month of June produced the best prediction ($R^2 = 0.633$), while in the year 2020 with floods, June also had the best prediction ($R^2 = 0.660$) (Xu et al., 2026). Incorporation of the topographic, climatic, and physicochemical characteristics of the soil increased the predictive efficiency up to $R^2 = 0.708$ and $RMSE = 5.577$ g/kg, surpassing remote sensing models, where the prediction with the least uncertainty occurred in 2021 (mean uncertainty = 2.67 g/kg).

The Contribution of SOM to Soil Health: Physical, Chemical, and Biological Roles

Influence on Soil Physical Characteristics

Organic matter addition to soil positively affects its physical characteristics, enhancing plant growth and agriculture (Gurmu, 2019). It is essential to note that organic matter contributes to the stability of aggregates of various sizes and prevents their disintegration in wet conditions, primarily through bonding of particles. Aggregate stability, which increases with an increase in SOM, promotes soil porosity, reducing bulk density. Gurmu, (2019), stating that soil organic carbon increases bulk density in arctic tundra soils quadratically. The major impact of SOM on soils is that it alters their water-holding capacity properties. The reason for this is that SOM helps to enhance the soil water-holding capacity by reducing soil bulk density and enhancing the total porosity, altering the soil aggregate size distribution, and improving soil surface area absorbency (Gurmu, 2019).

Effects on Soil Chemical Properties

Humus is usually responsible for between 50 and 90% of the ion-exchange ability of soil. Just like the clay fraction, organic soil materials adsorb nutrient cations (potassium, calcium, and magnesium) in an easily exchangeable form that allows plants to absorb it while preventing it from leaching out of the soil profile when water seeps through it (Gurmu, 2019). According to Kaplan and Estes (1985) as cited by (Gurmu, 2019), an additional 1% increment in SOM in a dry weight basis causes a $1.7\text{cmol/CECkg}^{-1}$ increase in soil cations. The pH-dependent cation exchange capacity is an extremely significant contribution of SOM to agriculture because it regulates nutrient availability in the soil solution.

Effects on Soil Biological Properties

The contents of SOM impact soil biological properties by affecting N-mineralizing bacteria, N-fixing bacteria, mycorrhizal fungi, and microbial biomass (Gurmu, 2019). Microbial biomass facilitates different vital activities in soil, such as nutrient mineralization, nutrient cycling, and SOM decomposition. Microbial biomass carbon and nitrogen form less than 1%–3% of the total soil carbon and around 5% of total soil nitrogen, respectively; however, they remain the biologically most active forms of SOM (Gurmu, 2019).

Climatic Changes, Soil Microbiome, and SOM

Direct Effects of Climatic Changes on SOM

The effects of climatic changes on soils have been known to be a slow and intricate process. Not only do soils have to undergo direct changes in their environment due to climatic changes, such as increased rate of soil organic matter decomposition because of rising temperatures and indirectly from soil moisture content changes, but they are also one of the sources of greenhouse gases that contribute to climatic changes (Shah et al., 2022). Higher temperatures lead to higher rates of soil organic matter decomposition, resulting in the loss of

SOM and soil organic carbon. The reduction in the quantity of soil carbon negatively impacts other soil properties.

Climate Change and Soil Microbiome Stability

Climate change is another major issue in relation to its effect on the stability and functioning of the soil microbiome. This refers to the community stability which is defined by one or more key measures including stability measures of resistance (not affected by any disturbances), resilience (returning to an equilibrium state) and functional redundancy (Shah et al., 2022). The reaction of microbes to climatic changes expected in the future in terms of increased carbon dioxide concentrations, temperature increase, droughts, irregular precipitation, and increased fire frequencies affect both the community and its ecosystem functions (Shah et al., 2022).

Management Practices for Improving SOM

Conservation Tillage and Crop Rotation: Management practices that improve SOM include the use of various organic materials including the use of cover crops and crop rotations among others. Many studies reveal that tillage has negative impacts on soil aggregates since it enhances the mineralization of OM in addition to subjecting the soil aggregates to more impact energy from raindrops. However, conservation or no-tillage improves the accumulation of SOM since there is little mixing of the soils (Gurmu, 2019). The practice of crop rotations has significant benefits in relation to soil characteristics such as increased soil carbon and a diversity of plant residues compared to monoculture systems. Levels of soil carbon and nitrogen were higher in maize-oats-clover rotation and lower in maize mono-cropping.

Organic Amendments and Biofertilizers: The use of microbial inocula containing Diazotrophs such as *Rhizobium* spp., *Bradyrhizobium* spp., *Azospirillum* spp., and Cyanobacteria is noted to enhance soil fertility, plant growth, crop yield, and nutrient quality (Shah et al., 2022). PSBs and AM fungi contribute to phosphorus uptake by plants, phosphate solubilization, and phosphorus hydrolysis, thus decreasing reliance on synthetic fertilizers while increasing SOM via improved root growth and biomass formation (Shah et al., 2022). Bioengineered bacteria serve as a novel strategy to enhance stress resistance in plants and nutrient cycling to maintain food production amid the impacts of climate change. Utilizing bioengineered bacteria that are stress-resistant as inoculants allows their application for enhanced nutrient cycling. In addition, strategies including volatile organic compound synthesis, phytohormone biosynthesis, ACC deaminase, siderophores, and quorum sensing can be harnessed by soil bacteria to remediate contaminated soils (Shah et al., 2022).

Minimizing SOM Losses: SOM losses may be minimized by limiting the loss of crop residues during harvesting, minimizing SOM losses due to erosion caused by water and wind, and preventing carbon losses by increasing microbial respiration rates. Erosion-related SOM losses are greater than SOM losses attributed to cultivated soils – usually 5 to 50 Mg/ha/year – because SOM is usually more abundant in the surface layer where erosion is common.

Conclusion

SOM is not only a constituent of soil but the unseen force that links soil health, productivity, and sustainability. As mentioned by Gurmu, (2019), SOM is the optimal indicator of soil quality. Its physical, chemical, and biological properties work as a virtuous cycle where aggregation helps in water retention, promoting microbial activity that leads to nutrient cycles and ultimately SOM production. However, changes in climate pose severe challenges to SOM functions; the increased temperature speeds up decomposition, drought changes microbial population, flooding alters the distribution of SOM, and increased CO₂ causes rhizosphere activity (Shah et al., 2022). Nevertheless, the soil microbiome's resilience via redundancy provides a natural buffer to climate change that needs proper management.

References

1. Dong, Z., Wang, N., Liu, J., Xie, J., & Han, J. (2021). Combination of machine learning and VIRS for predicting soil organic matter. *Journal of Soils and Sediments*, 21(7), 2578–2588. <https://doi.org/10.1007/s11368-021-02977-0>
2. Gurmu, G. (n.d.). Soil Organic Matter and its Role in Soil Health and Crop Productivity Improvement. *Soil Health and Crop Productivity Improvement. Acad. Res. J. Agri. Sci. Res*, 7(7), 475–483. <https://doi.org/10.14662/ARJASR2019.147>
3. Sewpersad, T., Xulu, S., & Gebreslasie, M. (2024). The assessment of soil organic matter in the KwaZulu-natal province of South Africa and its relationship to spectroscopy data. *Geocarto International*, 39(1). <https://doi.org/10.1080/10106049.2024.2361702>
4. Shah, A. M., Khan, I. M., Shah, T. I., Bangroo, S. A., Kirmani, N. A., Nazir, S., Malik, A. R., Aezum, A. M., Mir, Y. H., Hilal, A., & Biswas, A. (2022). Soil Microbiome: A Treasure Trove for Soil Health Sustainability under Changing Climate. In *Land* (Vol. 11, Number 11). MDPI. <https://doi.org/10.3390/land11111887>
5. Xu, Y., Chu, N., Luo, C., & Liu, H. (2026). Quantitative estimation of soil organic matter content in black soil region under varying climatic conditions using optical radar remote sensing technology. *International Journal of Digital Earth*, 19(1). <https://doi.org/10.1080/17538947.2026.2646388>