AGRIALLIS

SCIENCE FOR AGRICULTURE AND ALLIED SECTOR

VOLUME 7
ISSUE 9

SEP. 2025

A Monthly "e" Magazine

Online ISSN 2582-368X

www.agriallis.com

Growing seed

Editorial Board

Contents

Article Id
AL04470

BIOFORTIFICATION IN CROPS: GROWING NUTRITION FOR THE FUTURE

[1]Jagatjhuti Datta*, [1]Subhradip Bhattacharjee and [1]Sahanob Nath

Email

jagathjyoti@gmail.com

[1]Growing Seed, Dharmanagar, North Tripura- 799250, India

In a world where more than two billion people suffer from hidden hunger—micronutrient deficiency that often goes unnoticed—improving the nutritional quality of food crops has become a global priority. Traditional interventions like supplements and food fortification have helped, but they rely heavily on continuous supply chains, infrastructure, and behavioural change. This is where biofortification steps in as a quiet game-changer.

Biofortification means enhancing the nutrient content of food crops *as they grow*, either through selective breeding, modern biotechnology, agronomic practices, or microbiome-based strategies. Instead of adding nutrients later, biofortified crops are designed to naturally contain higher levels of vitamins and minerals such as iron, zinc, vitamin A, or amino acids. Since farmers can grow them like any other crop, biofortification becomes a sustainable long-term solution—especially for low-income populations that rely heavily on staple foods.

In recent years, advances in genomics, metagenomics, genome editing, and precision agriculture have opened new pathways for more targeted and efficient biofortification. These innovations are reshaping how scientists understand plant nutrition and paving the way for crops that address both malnutrition and climate resilience.

Technologies Driving Biofortification

Biofortification isn't a single method—it's a broad set of approaches. Here are the major technological pillars:

1. Conventional Breeding

Perhaps the most widely adopted method, it uses natural variation within crop species to select high-nutrient varieties.

Examples include:

- Iron-rich beans
- Zinc-rich wheat
- Pro-vitamin A sweet potato

Breeders cross high-nutrient varieties with high-yielding cultivars, using marker-assisted selection to speed up the process.

2. Genetic Engineering

Genetic modification (GM) allows direct insertion or modification of genes responsible for nutrient synthesis, transport, or storage.

Key advantages include:

- Ability to introduce traits not found naturally in the species
- Faster development
- Higher nutrient enhancement levels

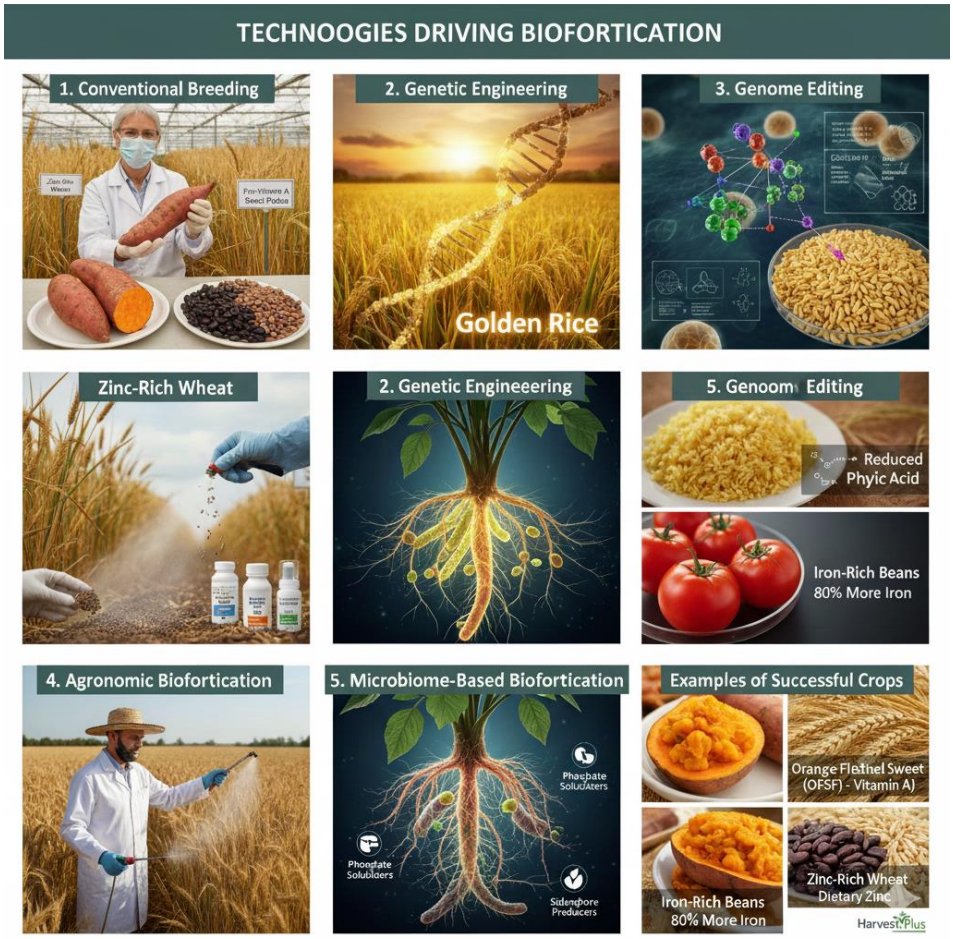
A famous example is Golden Rice, engineered with genes from maize and a soil bacterium to produce β-carotene.

3. Genome Editing (CRISPR/Cas9 and Others)

Gene editing technologies allow precise edits without introducing foreign DNA. For biofortification, genome editing can:

- Increase iron and zinc transporter activity
- Reduce anti-nutrients like phytic acid
- Upregulate vitamin-synthesis pathways
- Modify storage proteins

For instance, CRISPR-edited tomatoes have been developed with higher GABA content, and rice with reduced phytic acid has been created using targeted mutations.



4. Agronomic Biofortification

This method uses fertilizers or soil amendments containing micronutrients. Examples include:

- Zinc sulphate application in wheat
- Selenium enrichment through soil or foliar sprays
- Silicon or boron supplements to enhance nutrient mobility

It's cost-effective and can be implemented quickly, though it requires regular inputs.

5. Microbiome-Based Biofortification

With insights from metagenomics, researchers are increasingly using microbes as biofortification agents.

These include:

- Arbuscular mycorrhizal fungi to improve phosphorus and zinc uptake

- Phosphate-solubilizing bacteria for improving micronutrient mobility
- Siderophore-producing bacteria to increase iron availability

Microbial inoculants can be applied as seed coatings, soil amendments, or root-zone treatments.

Examples of Successful Biofortified Crops

Here are some widely recognized success stories:

1. Golden Rice

- Enriched with vitamin A (β-carotene)
- Helps address vitamin A deficiency in Asia
- Developed through genetic engineering

2. Orange-Fleshed Sweet Potato (OFSP)

- High in β-carotene
- Widely adopted in Africa
- Produced through conventional breeding

3. Iron-Rich Beans

- Contain up to 80% more iron
- Released by HarvestPlus in several African countries

4. Zinc-Rich Wheat

- Popular in India, Pakistan, and Bangladesh
- Increases dietary zinc intake significantly

5. Selenium-Enriched Wheat and Rice

- Achieved through agronomic fortification
- Helps reduce selenium deficiency in China and Finland

6. CRISPR-Edited Rice

- Modified to reduce phytic acid (an anti-nutrient)
- Improves bioavailability of iron and zinc

These success stories demonstrate that biofortification can work across crops, ecosystems, and technologies.

Conclusion

Biofortification represents one of the most promising strategies for fighting hidden hunger in a sustainable, farmer-friendly way. As climate change, soil degradation, and population growth make food security more challenging, enhancing the nutritional quality of staple crops becomes not just desirable but essential.

Genome editing are taking biofortification into a new era—where nutrient-dense crops can be tailored with precision, supported by beneficial microbes, and adapted to the environment in smarter ways. While some debate continues around genetically engineered biofortified crops, the overall global momentum—from HarvestPlus to CGIAR to national agricultural programs—signals that biofortification is here to stay.

Ultimately, combining traditional knowledge, modern biotechnology, can build a future where every meal delivers better nutrition, especially for vulnerable communities. Biofortification isn't just a technical innovation—it's a social investment in healthier generations.

References

HarvestPlus (2024). *Biofortification: Improving Nutrition Through Agriculture*.

Bouis, H., & Saltzman, A. (2017). "Improving nutrition through biofortification." *Global Food Security*.

Garg, M. et al. (2018). "Biofortification: A sustainable approach to improve food security." *Plant Biotechnology Journal*.

WHO (2023). *Micronutrient Deficiencies—Global Overview*.

Singh, U. et al. (2022). "Metagenomics and the plant microbiome: A new frontier in nutrient-rich crop development." *Frontiers in Microbiology*.

Pillai, S. et al. (2020). "CRISPR-based strategies for micronutrient enhancement in crops." *Trends in Plant Science*.

Article Id
AL04471

BRIDGING TRADITION AND SCIENCE: INDIGENOUS KNOWLEDGE IN SUSTAINABLE FARMING

[1]Anjali M. C.*, [2]Anand S., [2]Manoj Kumar H. S. and [2]Ravikumar D.

Email
anjalimc121@gmail.com

[1]Department of Soil Science, University of Agricultural Sciences, Mandya, Karnataka, India

[2]Department of Soil Science, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga, India

Indigenous Technical Knowledge (ITK) represents a treasure trove of eco-friendly farming practices honed over centuries by Indian farmers. These time-tested methods demonstrate remarkable sophistication in addressing contemporary agricultural challenges while maintaining ecological harmony. Traditional soil enrichment techniques like ash application and green manuring enhance fertility without chemical inputs, while innovative water management systems such as pitcher irrigation showcase precise moisture delivery. As modern agriculture grapples with sustainability crises, these indigenous systems offer valuable lessons in resilience, particularly for smallholders in climate-vulnerable regions. The documented synergy between ITK and scientific approaches points toward a holistic paradigm for sustainable food production that honors traditional wisdom while embracing innovation.

Indigenous Technical Knowledge (ITK) refers to the traditional knowledge and practices that have been developed by local communities over generations through observation, experimentation and adaptation to their environment. In the context of Indian agriculture, ITK has played a crucial role in ensuring food security, environmental sustainability and resilience against climate variations (Srinivasarao et al., 2021). These indigenous practices are deeply rooted in cultural traditions and have helped farmers manage natural resources efficiently without relying heavily on external inputs such as synthetic fertilizers and pesticides.

Role of Indigenous Knowledge in Indian Agriculture

India has a rich heritage of agricultural wisdom, which varies across its diverse agro-climatic regions. Indigenous knowledge has been instrumental in soil conservation, water management, pest control and crop rotation (Melash *et al.*, 2023). Farmers have developed

time-tested techniques that ensure sustainability and enhance productivity while maintaining ecological balance.

Soil and Crop Management Practices

One of the core aspects of Indigenous Technical Knowledge in agriculture is soil fertility management. Farmers in different regions have used organic amendments such as farmyard manure, green manure and compost to enhance soil productivity.

a) Mixed cropping and crop rotation: Traditional Indian farmers practice intercropping and mixed cropping to maximize yield and maintain soil fertility. Examples include the cultivation of pulses with cereals to naturally fix nitrogen in the soil.
b) Use of neem and other natural fertilizers: The application of neem leaves and neem oil as bio-fertilizers and pesticides is a well-known indigenous practice to protect crops from pests while maintaining soil health.
c) Charcoal and wood ash in soil: Farmers use wood ash and charcoal as soil amendments to enhance soil pH and provide essential nutrients like potassium (Fig. 1).
d) Applying fish cleaning water at the base of leguminous (bean) and cucurbits to get benefits.
e) Detopping aush rice plants when the vegetative growth is vigorous.
f) Hand pollination of kakrol (Spiny gourd), cucurbit flowers for getting around and unique fruits.

Fig. 1: Wood ash as a source of fertilizer

Water Conservation and Management

In regions prone to water scarcity, indigenous water conservation techniques have been developed to optimize irrigation and ensure sustainability.

a) Bamboo drip irrigation: Practiced in Meghalaya and other northeastern states, this method efficiently channels water to plant roots using bamboo pipes, reducing water wastage.
b) Zabo system: Practiced in Nagaland, this method involves collecting rainwater in small ponds and using it for irrigation, preventing soil erosion and ensuring water availability.
c) Phad system: This ancient irrigation practice in Maharashtra involves constructing embankments along rivers to store water and divert it to agricultural fields.
d) Pitcher irrigation system: Earthen pots are buried near the rootzone and water is filled in it, water gradually seeps out is made available to the plants (Fig. 2).

Fig. 2: Pitcher irrigation system

Pest and Disease Control

Indigenous methods of pest and disease management rely on botanical extracts and biopesticides, reducing dependency on chemical inputs.

a) Use of cow urine and dung: Cow urine mixed with plant extracts is used as an effective organic pesticide against various pests and fungal infections. Preparations like jeevamruta and panchagavya are found to be very effective (Fig. 3).
b) Marigold as a pest repellent: Farmers plant marigold flowers around crop fields to repel harmful insects such as nematodes and aphids.
c) Fermented buttermilk spray: In many parts of India, farmers use fermented buttermilk as a fungicide to prevent fungal diseases in crops.
d) Spreading tobacco dust over the field to control insects.
e) Setting up bamboo sticks or branches of trees in the rice field to sit down the birds and eat away insects helps to control insect infestation.
f) Spraying neem solution on the vegetables to control insects.
g) Intercropping garlic and potato to minimize pest attack.
h) Spreading Ash in the vegetable field to control aphids.

i) Spraying cow dung mixed water in the field to prevent the attack of cattle and goats.

Fig. 3: Jeevamrutha and Panchagavya

Seed Preservation and Indigenous Crop Varieties

Indian farmers have traditionally conserved indigenous seed varieties known for their resistance to local pests and climatic conditions.

a) Navdanya (Nine Seeds) tradition: Many farmers in states like Uttarakhand practice seed saving and exchange to maintain biodiversity.
b) Saltwater seed selection: A traditional practice in coastal regions where farmers immerse paddy seeds in saltwater to select high-quality seeds that sink (Khan et al., 1997).
c) Sacred groves and community seed banks: Many tribal communities maintain community seed banks to preserve heirloom crop varieties and ensure resilience against climate change.

Agroforestry and Traditional Farming Systems

a) Home gardens and forest farming: Many tribal communities integrate agriculture with forestry, cultivating a mix of trees, shrubs and food crops to enhance biodiversity and sustain livelihoods.
b) Jhum cultivation: Practiced in the northeastern states, shifting cultivation involves clearing small patches of land for farming while allowing previous fields to regenerate, maintaining ecological balance.

Relevance and Modern Integration

While indigenous knowledge systems have proven to be sustainable, they are often overlooked in favor of modern agricultural practices. However, recent efforts by the Indian

government, NGOs and agricultural research institutions aim to integrate ITK with scientific advancements to promote sustainable farming.

a) Organic farming movements: States like Sikkim have embraced organic farming, drawing heavily from traditional knowledge.
b) National Innovations on Climate Resilient Agriculture (NICRA): This initiative by the Indian Council of Agricultural Research (ICAR) integrates ITK with modern climate-resilient farming practices.
c) Participatory research and farmer field schools: These initiatives encourage knowledge exchange between scientists and traditional farmers, preserving and improving indigenous techniques.

Conclusion

Indigenous Technical Knowledge in Indian agriculture is a valuable asset that has sustained rural communities for centuries. As environmental challenges such as climate change and soil degradation threaten modern farming systems, integrating ITK with contemporary scientific research can offer innovative solutions for sustainable agriculture. Recognizing and promoting these traditional practices can enhance food security, preserve biodiversity and contribute to a more resilient and self-reliant agricultural system in India.

References

Srinivasarao, C., Lakshmi, C. S., Kundu, S., Kumar, G. R., Somashekar, G., Manasa, R., ... & Pratibha, G. (2021). Indigenous technical knowledge for enhanced agronomic productivity and soil health of small holder farmers in Tropical India. *Climate Change and Environmental Sustainability*, *9*(1), 1-13.

Melash, A. A., Bogale, A. A., Migbaru, A. T., Chakilu, G. G., Percze, A., Ábrahám, É. B., & Mengistu, D. K. (2023). Indigenous agricultural knowledge: A neglected human based resource for sustainable crop protection and production. *Heliyon*, *9*(1).

Khan, M. S. A., Hamid, A., & Karim, M. A. (1997). Effect of sodium chloride on germination and seedling characters of different types of rice (Oryza sativa L.). *Journal of Agronomy and Crop Science*, *179*(3), 163-169.

Article Id
AL04472

HOW GOA'S AGRICULTURE SECTOR IS GROWING AND CHANGING

[1]Shripad Bhat* and [1]Paramesha V

Email

shripadsmail@gmail.com

[1]ICAR-Central Coastal Agricultural Research Institute, Goa, India

Agriculture is an important sector in Goa's economy. Though the contribution of agriculture and allied sector is about 5.40%, it provides livelihood opportunities for substantial number of farm families. It is important to know how this sector is changing relative to the state's economy to assess the resilience.

In 2020-21, both the agriculture and allied sectors and the overall Gross State Domestic Product (GSDP) of the state witnessed a decline, reflecting the broader economic impact (Table 1). However, since 2020-21, the GSDP data shows that agriculture, forestry and fishing sector has grown steadily. Fishing and Aquaculture sector also registered growth especially from 2022-23. The overall GSDP also showed steady growth since 2020-21.

Table 1: Gross State Domestic Product by industry of origin at constant prices (₹ in Lakh) - Base year 2011-12

Industry	2019-20	2020-21	2021-22	2022-23 (P)	2023-24 (Q)
Agriculture, forestry and fishing	**276380**	**263316**	**263841**	**290332**	**311316**
a) Crops	100060	98984	97877	102625	104678
b) Livestock	31670	29197	30212	30537	36687
c) Forestry and Logging	72286	64133	63369	69722	78131
d) Fishing and Aquaculture	72364	71002	72383	87448	91820
Gross State Domestic Product	**5481154**	**5260542**	**5316815**	**5986675**	**6413700**

Source: Economic Survey of Goa, 2024-25, P – Provisional Estimates, Q- Quick Estimates

The share of agriculture, forestry and fishing in Goa's economy remained stable at around 5.40% with marginal changes over the years (Table 2). Between 2019-20 and 2023-24, the share of fishing and aquaculture sector improved from 1.46% to 1.59% while the share of crops sector declined from 2.01% to 1.81%. The share of livestock sector remained stable at

0.64% while forestry and logging sector declined from 1.45% to 1.35%. These values indicate a gradual shift in the agriculture sector of Goa.

Table 2: Sector-wise % distribution of Gross State Domestic Product by industry of origin at constant prices - Base year 2011-12

Industry	2019-20	2020-21	2021-22	2022-23 (P)	2023-24 (Q)
Agriculture, forestry and fishing	**5.56**	**5.45**	**5.41**	**5.37**	**5.40**
a) Crops	2.01	2.05	2.01	1.90	1.81
b) Livestock	0.64	0.60	0.62	0.57	0.64
c) Forestry and Logging	1.45	1.33	1.30	1.29	1.35
d) Fishing and Aquaculture	1.46	1.47	1.49	1.62	1.59

The year-on-year growth shows that both the overall GSDP and agriculture, forestry and fishing sector contracted during 2020-21 mainly due adverse conditions posed by Covid-19. The decline ranged from -11.28% in forestry and logging to -1.07% in crops. Overall, the agriculture and allied sector shrank by -4.73% while the overall GSDP fell by -4.02% during 2020-21. However, growth recovered in the following years. By 2022-23, all segments of agriculture and allied sector recorded positive growth. During recent years, livestock, forestry & logging and fishing & aquaculture registered higher growth indicating strong performance.

Table 3: Percent growth over the previous year of Gross State Domestic Product by industry of origin at constant prices - Base year 2011-12

Industry	2019-20	2020-21	2021-22	2022-23 (P)	2023-24 (Q)
Agriculture, forestry and fishing	**4.61**	**-4.73**	**0.20**	**10.04**	**7.23**
a) Crops	-10.31	-1.07	-1.12	4.85	2.00
b) Livestock	72.31	-7.81	3.48	1.08	20.14
c) Forestry and Logging	37.07	-11.28	-1.19	10.03	12.06
d) Fishing and Aquaculture	-11.24	-1.88	1.94	20.81	5.00
Gross State Domestic Product	**3.30**	**-4.02**	**1.07**	**12.60**	**7.13**

Growth rate and coefficient of variation of different sectors for the period 2019-20 to 2023-24 are given in Table 4. The coefficient of variation in crop sector was low (2.75%) indicating stable performance (Table 4). The exponential growth rate in fishing and aquaculture was 7.09% which was statistically significant, despite higher variability (12.46%). The overall

GSDP growth was 4.54%, which was statistically significant, with moderate variability (8.69%) indicating steady expansion of the state economy during 2019-20 to 2023-24.

Table 4: Exponential growth rate (%) and coefficient of variation (%) of Gross State Domestic Product at constant prices during 2019-20 to 2023-24 - Base year 2011-12

Industry	Exponential growth rate (%)	Coefficient of Variation (%)
Agriculture, forestry and fishing	**3.41**	**7.19**
a) Crops	1.27	2.75
b) Livestock	3.45	9.30
c) Forestry and Logging	2.42	8.77
d) Fishing and Aquaculture	7.09**	12.46
Gross State Domestic Product	**4.54***	**8.69**

* Significant @ 10% level, ** significant @ 5 % level

Conclusion

Overall, from 2019-20 to 2023-24, the GSDP grew by 4.54% and fishing and aquaculture sector registered a growth rate of 7.09%. Performance of the crop sector was stable. These trends highlight the gradual changes in Goa's agriculture over the years, supporting the state's overall economic growth.

Reference

Economic Survey 2024-25, Directorate of Planning, Statistics and Evaluation, Porvorim, Goa https://www.dpse.goa.gov.in/Economic-Survey-2024-25.pdf

Article Id
AL04473

SYNTHETIC APERTURE RADAR IN AGRICULTURE: APPLICATIONS, ADVANCES, AND FUTURE PROSPECTS

[1]Subhradip Bhattacharjee* and [1]Basavareddy

Email

subhradip25@gmail.com

[1]ICAR- Central Coastal Agricultural Research Institute, Goa, India

Agricultural systems increasingly demand continuous, high-resolution monitoring to support food security, climate adaptation and precision farming. Traditional field-based observations, although accurate, are spatially limited and resource-intensive, while optical satellite remote sensing is frequently constrained by cloud cover, haze and revisit gaps-challenges that are particularly acute in monsoon-dominated and tropical agricultural regions. Synthetic Aperture Radar (SAR) addresses these limitations through active microwave sensing, enabling data acquisition independent of sunlight and largely unaffected by clouds, smoke or atmospheric conditions. This makes SAR uniquely suited for year-round agricultural surveillance, especially during critical growth phases that coincide with persistent cloud cover.

SAR backscatter is sensitive to biophysical properties such as soil moisture, surface roughness, crop structure, biomass and flooding status. These sensitivities allow systematic monitoring of sowing patterns, growth stages, irrigation cycles, harvest timing and post-harvest management across diverse landholdings-from smallholder farms to industrial cropping systems. Furthermore, modern SAR missions, such as Sentinel-1 and upcoming dual-band systems like NISAR, provide frequent, high-resolution observations that can be integrated with optical, thermal and ground-based datasets to enable advanced analytics including machine learning, data fusion and model-driven yield forecasting.

In this context, SAR is transitioning from a niche scientific tool to a foundational technology for climate-smart, data-driven agriculture and policy decision-making.

Fundamentals of Synthetic Aperture Radar

Synthetic Aperture Radar (SAR) is an active microwave remote sensing system that transmits electromagnetic pulses toward the Earth's surface and measures the energy scattered back to the sensor. Unlike passive optical instruments that rely on reflected sunlight, SAR

operates independently of illumination and can penetrate clouds, haze and smoke, making it well-suited for agricultural landscapes where critical growth stages coincide with monsoon or overcast conditions. SAR sensors are typically mounted on satellites or aircraft and operate in a side-looking geometry. High spatial resolution is achieved computationally by synthesizing a long virtual antenna from successive radar echoes collected along the platform's flight path- a principle known as *synthetic aperture processing*.

Several system parameters determine how SAR interacts with agricultural surfaces:

- Frequency/Wavelength Bands: X-band (~3 cm) responds to fine canopy features; C-band (~5–6 cm), used by missions such as Sentinel-1 and RISAT, captures both soil and crop canopy dynamics; L-band (~23 cm), deployed in missions like ALOS-2 and NISAR, penetrates deeper into vegetation and is advantageous for biomass and agroforestry monitoring.
- Polarization (VV, VH, HH, HV): Co-polarized channels are typically sensitive to soil moisture and surface scattering, while cross-polarized channels capture volume scattering from stems and foliage.
- Incidence Angle and Spatial Resolution: These influence sensitivity to roughness, moisture and canopy structure, often requiring normalization for large-scale analyses.

Together, these parameters determine the quantitative value of SAR for retrieving agricultural biophysical variables and building time-series analytics across seasons.

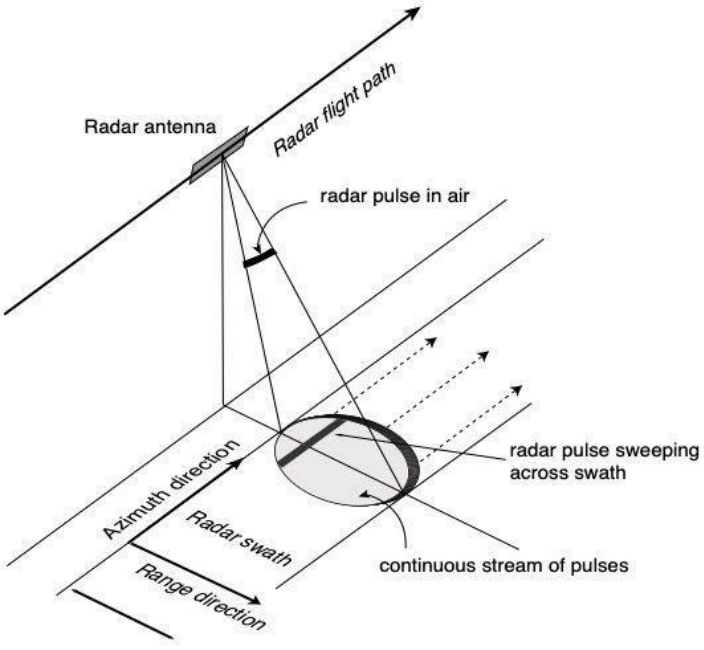


Fig. 1: working mechanism of SAR

SAR Interaction with Agricultural Targets

Agricultural landscapes present complex and rapidly changing microwave scattering environments where soil moisture, canopy architecture, residue cover and management practices jointly influence radar backscatter. Unlike natural forests, crop fields undergo fast phenological transitions-from bare soil to full canopy and back to harvested surfaces-resulting in distinct temporal signatures that can be exploited for crop monitoring, sowing date detection and growth-stage mapping.

Three dominant scattering mechanisms govern the SAR response over croplands:

- Surface Scattering: Predominant in early-season and post-harvest conditions when vegetation is sparse. Backscatter is largely driven by soil dielectric properties, which increase with moisture content, and by surface roughness influenced by tillage, ridging and crusting. Co-polarized channels (VV/HH) are particularly sensitive during this stage.
- Volume Scattering: As crops develop, stems, leaves and panicles introduce multiple scattering pathways within the canopy. Cross-polarized channels (VH/HV) capture this complexity and often correlate with biomass, leaf area index (LAI) and canopy height, although saturation may occur at high biomass levels.
- Double-Bounce Scattering: Occurs when upright vegetation overlays water or saturated soil, producing strong dihedral reflections. This mechanism is characteristic of flooded rice paddies, irrigated lowlands, or residue standing over wet soil and is highly useful for transplanting detection, irrigation tracking and flood mapping.

These mechanisms evolve seasonally, producing distinctive multi-temporal backscatter trajectories. For example, rice fields show sharp transitions during flooding and transplanting, whereas maize exhibits gradual volume-scattering peaks during rapid vegetative growth. Understanding these interactions is fundamental to deriving biophysical parameters and interpreting SAR-based agricultural models.

SAR Data Sources and Processing Pipelines for Agriculture

The operational use of SAR in agriculture has advanced rapidly due to the availability of open-access satellite missions, improved spatial and temporal resolutions, and scalable cloud-based processing environments. Sentinel-1 (C-band) has become the most widely used dataset globally because of its 6–12-day revisit cycle, dual-polarization capability, and free

access, making it suitable for crop mapping, flood monitoring, and soil moisture analytics. Other major missions include ALOS-2 (L-band) for biomass and agroforestry applications, TerraSAR-X (X-band) for fine structural monitoring, RADARSAT Constellation for agricultural compliance and disaster assessment, and India's RISAT-1A/EOS-04, which supports monitoring in monsoon-prone cropping regions. The upcoming NISAR mission, with systematic global L- and S-band coverage, is expected to significantly enhance retrievals of crop structure, residue cover, and perennial systems.

To derive meaningful agricultural insights, SAR data undergo a structured preprocessing chain: radiometric calibration to obtain backscatter coefficients (σ^0), speckle filtering to improve interpretability, terrain and geometric correction for accurate geolocation, and incidence-angle normalization to ensure consistency across tracks. Time-series stacking further enables phenology tracking, irrigation event identification, and change-detection analytics. These workflows are increasingly executed on platforms such as Google Earth Engine, SNAP, Open Data Cube, DIAS, Bhuvan, and custom machine-learning pipelines, reducing computational barriers and enabling near real-time agricultural monitoring.

Core Agricultural Applications of SAR

The distinctive sensitivity of radar backscatter to soil moisture, vegetation structure and hydrological conditions enables SAR to support a wide spectrum of agricultural applications, ranging from crop inventory and phenological monitoring to yield estimation and disaster loss assessment. As multi-temporal SAR datasets have become denser and more accessible, their role has shifted from exploratory research to operational crop intelligence systems used by governments, insurers and climate-risk platforms. The key application domains are summarized below.

Crop Type Mapping and Acreage Estimation

SAR time-series capture crop-specific backscatter trajectories arising from differences in planting dates, water regimes, canopy structure and harvest patterns. Rice paddies, for instance, show distinct double-bounce signatures during flooding and transplanting, whereas dryland crops such as maize and wheat exhibit gradual increases in cross-polarized backscatter during vegetative growth. These temporal fingerprints allow supervised machine-learning and phenology-based classification to discriminate crops even when optical imagery is unavailable due to cloud cover. Combined SAR–optical fusion further enhances separability in mixed or

fragmented landscapes, making SAR essential for national crop inventory schemes, food security assessments and policy-linked acreage reporting.

Crop Growth Monitoring and Phenology Detection

Because SAR captures structural and moisture-driven changes throughout the crop lifecycle, time-series signals can be used to identify phenological transitions such as sowing, transplanting, tillering, flooding, flowering and harvest. Transition points can be detected automatically using break-point algorithms, time-series smoothing models or state-space approaches. These phenological profiles support in-season monitoring, early-warning advisories, crop calendar validation and retrospective attribution of production variability to management or climate anomalies. Such capabilities are especially valuable in monsoon regions where optical observations are obstructed during critical growth phases.

Soil Moisture, Waterlogging and Irrigation Dynamics

Soil dielectric properties increase sharply with volumetric water content, making SAR-particularly co-polarized C- and L-band observations-highly sensitive to surface moisture under low to moderate vegetation cover. Retrieval approaches range from empirical regressions to physically based models such as the Water Cloud Model, with recent advancements integrating machine learning and multi-sensor fusion to reduce uncertainties in roughness, slope and vegetation attenuation. Time-series analysis also supports detection of irrigation cycles, canal water delivery, and post-rain infiltration patterns, enabling assessment of water-use efficiency, drought impacts and hydrological interventions. In flood-prone agroecosystems, SAR's ability to map inundation beneath vegetation can inform disaster assessment and relief planning.

Above-Ground Biomass and Yield Estimation

Cross-polarized backscatter is often correlated with biomass accumulation, canopy height and LAI during vegetative stages. At longer wavelengths (e.g., L-band), penetration through upper canopy layers enhances sensitivity to structural attributes of crops and agroforestry systems. Yield estimation frameworks increasingly combine SAR-derived biophysical metrics with process-based crop growth models, statistical regressions or hybrid deep learning architectures. These integrations support pre-harvest yield forecasting, carbon budgeting, residue assessment and monitoring of resource-use efficiencies, particularly where field data are limited or optical indices saturate at high biomass.

Damage Assessment and Extreme Events

SAR is widely used to detect and quantify agricultural damage caused by floods, cyclones, hailstorms, lodging, drought and pest outbreaks. Flood detection relies on strong backscatter drops over open water and characteristic dihedral returns when vegetation stands in inundated fields. Lodging events alter canopy geometry, causing distinct changes in coherence and backscatter intensity, enabling insurance-oriented crop loss estimation. Unlike optical sensors, SAR allows rapid assessment during cloudy emergency conditions, making it critical for disaster-response programmes, post-cyclone crop loss verification and climate-risk modelling.

Monitoring Tillage, Residue, and Conservation Agriculture

Radar is sensitive to surface roughness and the structural arrangement of residue cover, allowing detection of tillage intensity, mulch persistence and residue-burning events. C-band signals respond strongly to changes in surface scattering, whereas L-band observations help separate residue structure from soil moisture effects. These metrics support carbon-farming programmes, regenerative agriculture schemes, soil conservation compliance and greenhouse gas inventories. Combined with metadata on crop rotations and fertilizer management, SAR can contribute to monitoring, reporting and verification (MRV) systems for sustainability and carbon-credit frameworks.

Emerging Trends: From PolSAR and InSAR to Deep Learning and Data Fusion

Recent advancements in sensing technology and computational analytics are transforming SAR from a predominantly backscatter-based monitoring tool into a multidimensional framework for structural, biophysical and process-level agricultural inference. Polarimetric SAR (PolSAR) systems enable full polarization acquisition, allowing scattering decomposition into surface, dihedral and volume components. Metrics such as entropy, anisotropy, alpha angle and the Radar Vegetation Index (RVI) provide enhanced sensitivity to crop architecture, residue cover, canopy water content and biomass dynamics. Compact-pol systems now offer a cost-effective alternative to quad-pol acquisitions, expanding scalability for operational agricultural monitoring.

In parallel, Interferometric SAR (InSAR) and Polarimetric InSAR (PolInSAR) techniques exploit phase differences across time or polarization channels to retrieve canopy height, vertical structure and subtle terrain deformation linked to groundwater extraction, land

subsidence and irrigation cycles. These capabilities are particularly relevant for tree-based cropping systems, perennial agroforestry landscapes and carbon accounting frameworks. Dual-frequency, high-revisit missions such as NISAR are expected to further advance operational use of these techniques by enabling global, systematic L- and S-band observations.

Concurrently, the integration of SAR with deep learning, biophysical models and multisensor fusion platforms is enabling end-to-end agricultural intelligence pipelines. Combining SAR with optical, thermal, LiDAR, UAV and ground sensors enhances yield prediction, soil moisture retrieval and anomaly detection in cloud-prone regions. Access to scalable platforms-such as Google Earth Engine, Open Data Cube and national digital agri-stacks-is accelerating deployment of SAR-based products in crop insurance, sustainability certification and climate-resilience planning.

Challenges, Limitations, and Research Gaps

Despite its growing prominence in agricultural monitoring, several technical and operational limitations constrain the full-scale deployment of SAR-based analytics. A fundamental challenge lies in the non-unique relationship between backscatter and biophysical variables, as soil moisture, surface roughness and vegetation structure often produce overlapping signals, complicating inversion models. Saturation effects at high biomass, limited availability of quad-polarimetric data and uncertainties arising from incidence angle variation further constrain quantitative retrievals. Soil moisture estimation remains particularly challenging under dense canopies, necessitating multi-frequency sensing or physics-guided machine learning.

Operational constraints also persist. Speckle, layover and shadowing reduce interpretability in heterogeneous terrain, while the computational cost of processing large time-series datasets remains significant for institutions without high-performance infrastructure. Although cloud platforms reduce barriers, they require skilled personnel trained in microwave physics and data analytics-expertise that is still limited in agricultural agencies and extension systems, especially in smallholder-dominated regions.

A major research gap lies in the lack of harmonized ground-truth datasets for calibration and validation across diverse agro-ecological zones. Integrating SAR with crop models, IoT sensors and soil–plant simulations remains an emerging frontier, as does translating SAR-derived indicators into actionable, farmer-friendly advisories. Addressing these gaps is

essential for transitioning SAR from scientific potential to operational agricultural decision-making.

Conclusion

As agriculture confronts the twin pressures of climate instability and rising production demand, SAR is becoming integral to digital agrometeorology, landscape monitoring and climate-smart decision support. Its ability to capture soil moisture dynamics, inundation, phenology and canopy structure under persistent cloud cover makes it uniquely suited for monsoon-dominated and tropical farming systems, where traditional optical monitoring frequently fails. The advent of high-revisit missions such as Sentinel-1 and dual-frequency systems like NISAR will expand the spatial and temporal resolution of agricultural observations, particularly in perennial horticulture and agroforestry domains where canopy penetration and structural retrieval are essential.

The future of SAR lies not only in improved sensors but in full eco-informatic integration, where radar signals merge with optical, thermal, UAV, IoT and ground-truth datasets to create operational crop intelligence pipelines. With machine learning, biophysical modelling, and automated change detection, SAR can support real-time crop insurance validation, carbon accounting, regenerative agriculture monitoring and resource-use efficiency assessments. Unlocking its full potential, however, will require investments in capacity building, open infrastructures, and harmonized field datasets. If these barriers are addressed, SAR will serve as a cornerstone technology for resilient, transparent and data-driven agricultural systems.

References

Oliver, C., & Quegan, S. (2004). *Understanding synthetic aperture radar images*. SciTech Publishing.

Chen, X., Dong, Z., Zhang, Z., Tu, C., Yi, T., & He, Z. (2024). Very high resolution synthetic aperture radar systems and imaging: A review. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *17*, 7104-7123.

Hashemi, M. G., Jalilvand, E., Alemohammad, H., Tan, P. N., & Das, N. N. (2024). Review of synthetic aperture radar with deep learning in agricultural applications. *ISPRS Journal of Photogrammetry and Remote Sensing*, *218*, 20-49.

Hashemi, M. G., Jalilvand, E., Alemohammad, H., Tan, P. N., & Das, N. N. (2024). Review of synthetic aperture radar with deep learning in agricultural applications. *ISPRS Journal of Photogrammetry and Remote Sensing*, *218*, 20-49.

Mardan, M., & Ahmadi, S. (2021). Soil moisture retrieval over agricultural fields through integration of synthetic aperture radar and optical images. *GIScience & Remote Sensing*, *58*(8), 1276-1299.

Robertson, L. D., McNairn, H., van der Kooij, M., Jiao, X., Ihuoma, S., & Joosse, P. (2023). Monitoring autumn agriculture activities using Synthetic Aperture Radar (SAR) and coherence change detection. *Heliyon*, *9*(6).

Arslan, İ., Topakcı, M., & Demir, N. (2022). Monitoring maize growth and calculating plant heights with Synthetic Aperture Radar (SAR) and optical satellite images. *Agriculture*, *12*(6), 800.

Javali, A., Gupta, J., & Sahoo, A. (2021, August). A review on synthetic aperture radar for earth remote sensing: Challenges and opportunities. In *2021 Second international conference on electronics and sustainable communication systems (ICESC)* (pp. 596-601). IEEE.

Sorokin, A., Stepanov, A., Dubrovin, K., & Verkhoturov, A. (2024). Enhancement of Comparative Assessment Approaches for Synthetic Aperture Radar (SAR) Vegetation Indices for Crop Monitoring and Identification—Khabarovsk Territory (Russia) Case Study. *Remote Sensing*, *16*(14), 2532.

Zhan, P., Zhu, W., & Li, N. (2021). An automated rice mapping method based on flooding signals in synthetic aperture radar time series. *Remote Sensing of Environment*, *252*, 112112.

Article Id
AL04474

UNLOCKING THE HIDDEN WORLD BENEATH OUR FEET: METAGENOMICS IN SOIL SCIENCE

Sahanob Nath

Email
nathsahanob@gmail.com

Growing Seed, Dharmanagar, North Tripura, India

If you scoop up a handful of soil, it might look like just dirt—brown, crumbly, maybe a bit messy. But that tiny lump is actually one of the most complex ecosystems on Earth. A single gram of soil can hold billions of microorganisms—bacteria, fungi, archaea, viruses—most of which we've never seen or cultured in a laboratory. For decades, soil scientists struggled to understand these hidden life forms because only about 1% of soil microbes grow on traditional culture plates.

Then came metagenomics—a scientific game-changer. Suddenly, it became possible to explore the entire microbial community directly from environmental DNA, without needing to grow anything. Metagenomics has since transformed soil science, agriculture, climate research, and ecology. It helps us understand how soils function, how microbes support plant growth, how they cycle carbon and nitrogen, and how we might harness them to create more sustainable farming systems.

What Is Metagenomics?

Metagenomics is the study of genetic material recovered directly from environmental samples—soil, water, gut microbiomes, compost, or even deep-sea vents. Instead of focusing on single species, metagenomics analyses the entire community, or "microbiome."

The term itself reflects this idea:

- **Meta** = beyond
- **Genomics** = study of genomes

So, *metagenomics* literally means going beyond traditional genomics to explore mixed communities.

In soil science, this matters because:

- Soil microbes regulate nutrient cycling.
- They influence soil fertility and structure.
- They support plant roots and disease resistance.
- They play a major role in carbon sequestration and greenhouse gas emissions.

Metagenomics allows scientists to identify "who is there" and "what they can do" at the level of genes and pathways.

How Metagenomics Works: The Technology Behind the Magic

1. Sampling the Soil

Everything starts with carefully collecting soil samples. Soil is incredibly heterogeneous—microbial communities vary at centimeter scales. Scientists typically:

- Remove debris (roots, stones)
- Maintain sterile conditions
- Store samples in cold conditions to preserve DNA

2. DNA Extraction

This is one of the trickiest parts because:

- Soil contains humic acids and organic compounds that interfere with DNA
- Microbial cell walls vary widely in strength
- Soil particles can lodge between DNA fragments

Modern extraction kits use bead beating, detergents, and purification columns to get high-quality environmental DNA (eDNA).

3. Sequencing Technologies

Once DNA is extracted, it is sequenced using high-throughput platforms.

a) Amplicon Sequencing (16S/18S/ITS)

- Targets specific marker genes
- Provides taxonomic identity
- Cheaper and quicker
- Useful for community composition studies

Example: Using 16S rRNA sequencing to compare soil bacterial diversity between organic and conventional farms.

b) Shotgun Metagenomic Sequencing

- Sequences all DNA in the sample
- Provides functional genes, metabolic pathways, antibiotic resistance, etc.
- More powerful but more expensive

This method can identify:

- Nitrogen fixation genes (nifH)
- Methane oxidation pathways
- Cellulase enzymes for decomposition
- Stress tolerance genes

4. Bioinformatics Analysis

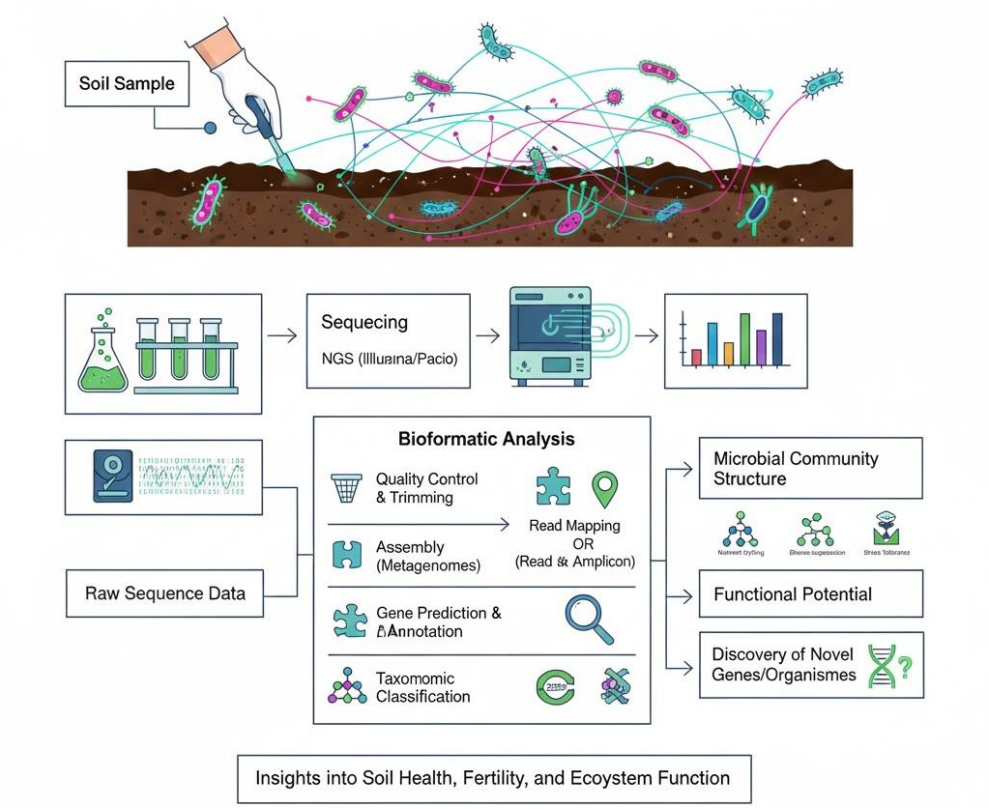
Raw sequences are useless until processed using computational tools.

Common steps:

1. Quality control (remove noise)
2. Filtering and trimming
3. Mapping sequences to databases
4. Functional annotation
5. Statistical analysis for diversity, richness, networks

Popular tools & databases:

- QIIME2
- MG-RAST
- Kraken2
- MetaPhlAn
- KEGG, MetaCyc, SILVA



This step often reveals thousands of microbial species—many previously unknown.

What Metagenomics Reveals About Soil Microbes

1. Soil Diversity Is Mind-Blowing

Metagenomic studies reveal:

- Over 50,000 microbial species per gram of soil in some forests
- Vast "microbial dark matter" (organisms with no known cultured relatives)
- Completely new bacterial phyla

This diversity regulates everything from decomposition to nutrient cycles.

2. Functions, Not Just Names

Metagenomics identifies the functional capacity of soil microbes.

Examples:

- Genes for nitrogen fixation (important for plant growth)
- Phosphorus solubilization genes
- Enzymes for breaking down lignin and cellulose

- Stress response genes for drought, salinity, heat

This helps scientists understand how soils adapt to climate change.

3. Plant–Microbe Interactions

Metagenomics uncovers beneficial microbes like:

- Rhizobia that fix nitrogen in legumes
- Mycorrhizal fungi that enhance nutrient uptake
- PGPR (Plant Growth-Promoting Rhizobacteria)

It also detects harmful pathogens early.

4. Soil Health & Pollution Remediation

Metagenomic analyses can identify microbes capable of:

- Breaking down pesticides
- Degrading hydrocarbons
- Removing heavy metals

This is crucial for bioremediation programs.

Real-World Examples

1. Metagenomics in Agriculture (India & Globally)

Researchers have shown that metagenomics can help:

- Identify microbial consortia that improve yields
- Understand why certain soils become infertile
- Develop biofertilizers tailored to local conditions

In Indian paddy soils, metagenomics revealed strong populations of:

- Methanogens (methane-producing microbes)
- Nitrogen cycling bacteria affected by flooding

This helps develop climate-smart rice cultivation.

2. Climate Change Studies

Permafrost soils contain huge stores of carbon. Metagenomic studies show which microbes wake up as temperatures rise and whether they release carbon as CO_2 or methane.

3. Desertification & Degraded Lands

In drylands, metagenomics helps identify:

- Microbes that tolerate extreme drought
- Soil crust communities that prevent erosion
- Beneficial organisms for land restoration

4. Forest Soil Microbiomes

Rich metagenomic datasets from tropical and temperate forests reveal:

- Massive fungal networks
- Nitrogen and phosphorus mineralizing microbes
- Enzymes involved in decomposition of leaf litter

These insights help in forest conservation and carbon budgeting.

Challenges in Soil Metagenomics

- Soil is extremely complex—DNA extraction is difficult.
- Many genes remain unannotated ("unknown function").
- Bioinformatics tools require high computational power.
- Distinguishing active vs. inactive microbes is challenging.
- Shotgun sequencing is still expensive for large-scale soil monitoring.

Despite these hurdles, the field is advancing rapidly.

Conclusion

Metagenomics has opened a new frontier in soil science. Instead of guessing what microbes do or trying to grow them in petri dishes, scientists can now peer directly into the genetic blueprint of entire soil ecosystems. This knowledge is transforming agriculture, climate research, ecology, and environmental management.

From improving crop yields to restoring degraded lands and understanding global nutrient cycles, metagenomics gives us a powerful toolkit to work with nature—rather than against it. As sequencing becomes cheaper and computational tools improve, metagenomics will become a cornerstone of sustainable land use and environmental policy.

The soil beneath our feet may look simple, but thanks to metagenomics, we now know it holds one of the richest and most dynamic worlds on the planet.

References

Handelsman, J. (2004). Metagenomics: Application of Genomics to Uncultured Microorganisms. *Microbiology and Molecular Biology Reviews*.

Prosser, J.I. (2015). Dispersing misconceptions and identifying opportunities for the use of metagenomics in soil microbial ecology. *Nature Reviews Microbiology*.

Torsvik, V., & Øvreås, L. (2002). Microbial diversity and function in soil. *Current Opinion in Microbiology*.

National Academies of Sciences. (2020). *Soil Microbiomes: Advancing Understanding of the Microbial World*.

Fierer, N. (2017). Embracing the unknown: disentangling the complexities of soil microbiomes. *Nature Reviews Microbiology*.