Chronicle of Bioresource Management 2026, 10(1): 016-021

Chronicle of Bioresource Management
An International E-magazine

March, 2026 **Popular Article**

DOI: HTTPS://DOI.ORG/10.23910/3.2026.6922

Technological Innovations for Agricultural Sustainability

Rohit B. Borate*, Y. S. Shivay, Kajal Das, Sk Asraful Ali, S. K. Prajapati, N. Saikia and L. P. Patil

Open Access

Corresponding Author

Rohit B. Borate

e-mail: rohitborate535@gmail.com

Citation: Borate et al., 2026. Technological Innovations for Agricultural Sustainability. Chronicle of Bioresource Management 10(1), 016-021. HTTPS://DOI.ORG/10.23910/3.2026.6922.

Data Availability Statement: Legal restrictions are imposed on the public sharing of raw data. However, authors have full right to transfer or share the data in raw form upon request subject to either meeting the conditions of the original consents and the original research study. Further, access of data needs to meet whether the user complies with the ethical and legal obligations as data controllers to allow for secondary use of the data outside of the original study.

Conflict of interests: The authors have declared that no conflict of interest exists.

Keywords:

Agricultural sustainability, artificial intelligence, conservation agriculture, precision agriculture, renewable energy

Article History

Article ID: CBM6922

Received on 09th January 2026

Received in revised form on 19th March 2026

Accepted in final form on 27th March 2026

Abstract

Agriculture is facing mounting challenges ranging from climate change, resource depletion, soil degradation, environmental pollution, declining productivity, and micronutrient deficiencies, while needing to feed a burgeoning global population. Technological innovations offer transformative solutions to enhance agricultural sustainability while minimizing environmental impacts. This article reviews key advancements across agronomic practices, digital tools, biotechnology, automation, and renewable energy that support resilient farming systems. Agronomic practices like conservation agriculture, direct-seeded rice, agroforestry and cover cropping improve soil health, conserve water, and reduce greenhouse gas emissions. Digital technologies, including precision agriculture, artificial intelligence, and IoT-based monitoring, enable efficient, data-driven resource use. Biotechnological innovations enhance crop resilience, nutritional quality, and input-use efficiency, while automation addresses labour constraints. Renewable energy integration reduces fossil fuel dependence, collectively promoting productive, climate-resilient, and sustainable agriculture for future food security.

1. Introduction

The world population, currently 7.6 billion, is projected to reach 8.6 billion by 2030, 9.8 billion by 2050, and 11.2 billion by 2100, intensifying the global food demand and underscoring the urgent need for sustainable agricultural practices. According to the Food and Agriculture Organization (FAO), global food production must increase by 70% by 2050 to meet the caloric needs of the expanding population. This translates to producing an additional 1.0 billion tonnes of cereals and 0.2 billion tonnes of meat annually. The environmental impact of agriculture is already significant, with the sector accounting for 24% of global greenhouse gas (GHG) emissions, largely due to deforestation, livestock, and fertilizer use (IPCC, 2021). If current practices remain unchanged, emissions are expected to rise in tandem with the increased food production needed to sustain the global population. Additionally, agriculture consumes about 70% of global freshwater resources

Author's Address

ICAR-Indian Agricultural Research Institute, Pusa Campus, New Delhi (110 012), India

annually, making it the largest user of freshwater. This dependency on water resources exacerbates challenges, especially in regions facing severe water scarcity. Soil degradation is another critical issue threatening agricultural productivity. Over 33% of the world's soil is moderately to highly degraded due to erosion, nutrient depletion, acidification, salinization, and chemical pollution. Without addressing these issues, maintaining soil fertility and productivity will become increasingly difficult. In addition to these problems, 30% of all food produced, which is approximately 1.3 billion tonnes is wasted each year, accounting for 8-10% of global GHG emissions and contributing to global food insecurity. To further exacerbate these challenges, climate change is predicted to reduce global crop yields by 10-25% by 2050 in key agricultural regions, particularly in developing countries. This scenario places even more pressure on agriculture to adapt and innovate sustainably (IPCC, 2021). Fortunately, technological innovations are offering new ways to address these challenges while promoting environmental sustainability. These innovations span various domains ranging from agronomic practices like conservation agriculture (CA) and direct-seeded rice (DSR) to cutting-edge advancements in biotechnology, automation, and renewable energy. Together, these technologies are reshaping agriculture to become more efficient, resilient, and environmentally friendly.

2. Agronomic Technological Innovations For Environmental Sustainability

2.1. Conservation agriculture (CA): a sustainable soil and water management approach

CA promotes environmental sustainability through three key principles:

• **Minimal soil disturbance:** Reducing tillage preserves soil structure, prevents erosion, retains organic matter, and enhances water retention and fertility.

• **Crop diversification:** Rotating crops, such as cereals and legumes, improves nutrient cycling, reduces pests and diseases, and boosts resilience to climate shocks.

• **Permanent soil cover:** Using cover crops or mulches protects soil from erosion, minimizes evaporation, and enhances organic content and water retention.

2.2. Direct-seeded rice (DSR)

DSR enhances environmental sustainability in rice cultivation by conserving water, reducing greenhouse gas emissions, and lowering labour costs.

• **Water conservation:** Uses up to 40% less water than flooded systems, benefiting water-scarce regions.

• **Reduced methane emissions:** Eliminates continuous flooding, lowering methane emissions and improving root growth through better water management.

• **Labour and cost savings:** Removes transplanting needs, reducing labour, time, tillage, soil compaction, and enabling flexible planting.

2.3. Agroforestry

Agroforestry integrates trees into farming systems, improving biodiversity, carbon storage, and soil health (Table 1).

• **Soil erosion control:** Deep roots stabilize soil, while canopies protect against heavy rainfall.

• **Biodiversity enhancement:** Supports wildlife, pollinators, and beneficial insects for better crop health.

• **Carbon sequestration:** Trees absorb and store CO_2 in biomass and soil, aiding climate mitigation.

2.4 *Minimum tillage and no-till farming*

Conservation tillage can enhance soil physical structure, improve water retention, protect moisture and boost crop yields.

• **Soil health improvement:** Enhance infiltration, root growth, and microbial activity, supporting nutrient cycling and organic matter buildup.

• **Erosion reduction:** Crop residues act as mulch, protecting soil from wind and water erosion.

• **Carbon sequestration:** By increasing soil organic matter, these practices contribute to carbon storage, helping mitigate climate change by capturing CO_2.

2.5 *Cover cropping*

Cover cropping is a conservation practice widely adopted by farmers to mitigate soil erosion while enhancing soil organic matter, nitrogen (N) cycling, soil structure, and reducing pest infestations and nitrogen leaching compared to systems without cover crops.

• **Soil erosion control:** Provides soil cover, reducing erosion and nutrient loss.

• **Improved soil fertility:** Leguminous cover crops fix nitrogen in the soil, naturally boosting fertility and reducing the need for synthetic fertilizers while preventing nutrient runoff into water systems.

• **Water retention:** Cover crops enhance soil permeability,

Table 1: Agronomic technological innovations for environmental sustainability

Location	Crop/Cropping system	Findings	Reference
Conservation agriculture			
New Delhi, India	Cotton-wheat	↑ 52% and 16% mean cotton and wheat yield, respectively under permanent broad bed + residue with 100% N than CT ↑ 53% and 17% mean cotton and wheat yield, respectively under permanent flat bed + residue with 100% N than CT ↑ 27.5% and 56% total organic carbon stock and system water productivity, respectively under permanent broad bed + residue with 100% N compared to CT	Das et al. (2025)
Haryana, India	Rice-wheat	↓ 9.8-10.7% and 11.1-11.3% bulk density in CA practiced for 8 and 12 years, respectively compared to CT ↑ 32 and 42.7% microbial biomass carbon and dehydrogenase activity, respectively in CA practiced for 8 years, 14.9 and 32.3% microbial biomass carbon and dehydrogenase activity, respectively in CA practiced for 12 years	Dash et al. (2025)
Direct-seeded rice (DSR)			
India	Rice (meta-analysis)	↑ 9.80% carbon sequestration, 20% nutrient availability ↑ N_2O emission ↓ 18% water use, 94.59% emissions of methane and 29.58% carbon dioxide ↓17.68% cultivation costs ↓ 8.98% yield	Kumara et al. (2026)
Agroforestry			
Jharkhand, India	Gamhar tree-based Agroforestry (Gamhar + arhar)	↑ 138.1% carbon stock, 136.64% carbon sequestration, 136.64% carbon credit, and 136.8% carbon price than sole Gamhar in 2016–2017 in pooled data	Kumar et al. (2024)
Dehradun (Uttarakhand), India	Bhimal (*Grewia optiva*) and Mulberry (*Morus alba*)-based agroforestry system under cowpea-toria based cropping systems and turmeric as ground storey crop	In the surface soil (0–15 cm), plots with mulberry + cowpea–toria recorded the highest C stock (21.35 Mg C ha^{-1}), comparable to mulberry + turmeric plots, while in the deeper soil layer (30–60 cm) they showed a significantly higher C stock (33.52 Mg C ha^{-1}) than the farmers' practice of cowpea–toria	Barman et al. (2025)
Minimum tillage and zero tillage			
ICAR-IIFSR (Modipuram, UP), India	Rice-wheat	14–21% energy savings in zero-till direct-seeded rice (ZTDSR) and Turbo Happy Seeder with residue retention (THSW + R) compared to puddled transplanted rice (PTR)-conventionally tilled wheat (CTW) systems. ZTDSR-THSW + R emerged as the most energy-efficient combination, recording the highest energy use efficiency (13.6) and the lowest system-specific grain energy (9.5 MJ kg^{-1}), reducing global warming potential by over 50%	Chaudhary et al. (2025)
Cover cropping			
Parana State, Brazil	Black oat, turnip, white oat, rye, white lupine, and common vetch	↓ Soil BD up to 5% ↑ Soil air-filled porosity up to 27% ↑ Saturated hydraulic conductivity up to 300%	Pott et al. (2023)

helping it absorbs and retain water, which reduces runoff and prevents soil degradation during dry periods.

3. Digital Technological Tools

Digital tools like precision agriculture enhance sustainability by improving monitoring and decision-making.

• **Soil and crop health monitoring:** Internet of Things (IoT) sensors and remote sensing provide real-time data on moisture, temperature, and nutrients, optimizing irrigation, fertilization, and pest control while reducing waste.

• **Artificial Intelligence (AI) and data analytics:** AI analyzes data to predict yields, optimize planting, and detect pests, improving decisions and productivity with lower environmental impact (Figure 1).

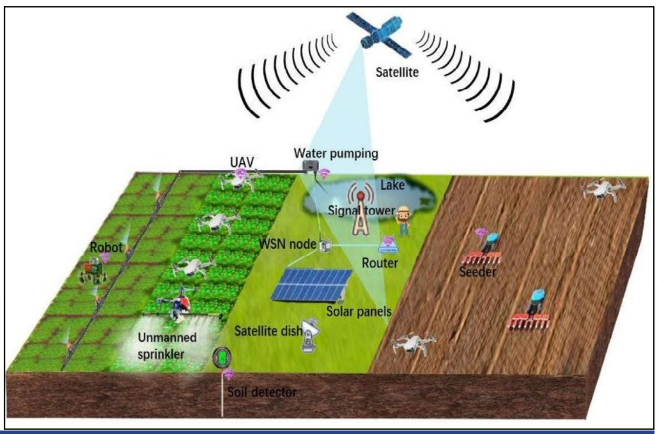


Figure 1: Digital tools for sustainable agriculture

• **Variable Rate Technology (VRT):** Applies inputs precisely as per field needs, reducing chemical runoff, water use, and improving sustainability.

4. Biotechnological Innovations

Biotechnology enhances crop production and sustainability by improving resilience, yields, and reducing harmful inputs. Through genetic engineering, crops withstand stress, resist pests, and grow in poor soils. Key advancements include:

a) Climate resilience: Genetically modified (GM) crops, like drought-tolerant maize and flood-resistant rice (e.g., Swarna Sub-1), survive extreme conditions, reducing losses in climate-affected areas.

b) Reduced agrochemical use: Crops like *Bt*-cotton and *Bt*-corn produce natural insecticides, lowering pesticide use, pollution, and related emissions.

c) Nutritional enhancement: Biofortification improves the nutritional content of crops to combat food security challenges. For instance, "Golden Rice" is enriched with Vitamin A to address deficiencies in developing countries.

d) Soil health: Genetically engineered nitrogen-fixing crops decrease reliance on synthetic fertilizers, preventing soil acidification, and waterway pollution, and maintaining soil fertility.

5. Automation

Automation and precision agriculture improve farming efficiency and sustainability using drones, robotics, GPS-guided machinery, and data analytics. These technologies optimize productivity while reducing resource waste (Table 2). Key developments include:

a) Optimized resource management: Automated irrigation systems, integrated with IoT sensors, monitor soil moisture levels and deliver water precisely where needed, reducing wastage and conserving freshwater

b) Enhanced efficiency: GPS-guided tractors and robots ensure precise planting, fertilizing, and harvesting, lowering fuel use, soil compaction, and resource consumption.

c) Pest and weed control: Drones with imaging and AI detect pests and weeds early; targeted spraying reduces chemical use and environmental impact.

d) Labour shortages: Automation performs tasks like harvesting, pruning, and seeding efficiently, maintaining productivity despite workforce decline.

6. Renewable Energy

Agriculture's dependence on fossil fuels for machinery, irrigation, and fertilizer production contributes significantly to GHG emissions. Transitioning to renewable energy sources such as solar, wind, and bioenergy offers a pathway to decarbonize the sector. Key approaches include:

a) Solar-powered irrigation: Solar pumps provide an eco-friendly alternative to diesel-based systems, especially in off-grid rural areas. They ensure reliable water access while reducing carbon emissions.

b) Bioenergy from agricultural waste: Crop residues and animal manure can be converted into biogas and bioethanol, reducing fossil fuel dependence. India's National Biogas and Manure Management Program promotes such initiatives.

Table 2: Potential of different automation technologies

Techniques	Remarks	Reference
Precision fertilizer application	This method alone can tap into an addressable market worth USD 65 billion by enhancing yields by 18%. The integration of tractor-mounted sensors, drones, satellites, and data analysis software will be pivotal in this regard	Goldman Sachs (2016)
Reduction in soil compaction	By employing a fleet of smaller, automated tractors, there is a potential to mitigate soil compaction, which has historically reduced yields by 15–20%. This approach alone presents a USD 45 billion market opportunity based on a projected 13% yield increment	
Precision irrigation	Modern irrigation systems paired with real-time water sensors can not only enhance yields by 10% but also curtail water wastage by up to 50%. This method taps into a USD 35 billion market	
Precision planting	With an expected 13% improvement in yields, the addressable market for this technology stands at USD 45 billion. The key here lies in the use of multi-hybrid planters and sophisticated data analysis tools	
Precision spraying	By optimizing pesticide and herbicide applications, yields can be boosted by 4%. This precise approach carves out an addressable market of USD 15 billion	

Biotechnology supports sustainability by managing GHG emissions, conserving resources, and reducing reliance on non-renewables. Agriculture can also generate renewable energy through biofuels. First-generation biofuels from sugarcane, maize, and soybean can reduce emissions by up to 42% when blended with petroleum fuels. Advances in next-generation biofuels from plant and algal sources improve efficiency, with lignocellulosic biomass offering strong potential.

c) Wind energy for farm operations: Small-scale wind turbines can power activities like water pumping and grain drying in areas with reliable wind resources.

d) Decentralized energy grids: Farms using solar panels and other renewable systems can support decentralized grids, reduce transmission losses and improve energy access.

Integrating renewable energy in agriculture reduces GHG emissions, lowers costs, and enhances sustainability.

7. Conclusion

Technological innovations are essential for sustainable agriculture, improving productivity while reducing environmental impacts. Advances in agronomy, precision farming, biotechnology, irrigation, renewable energy, and digital tools enhance resource efficiency and climate resilience. However, wider adoption requires investment in research, infrastructure, and supportive policies, along with collaboration among governments, industries, and institutions to ensure a sustainable future.

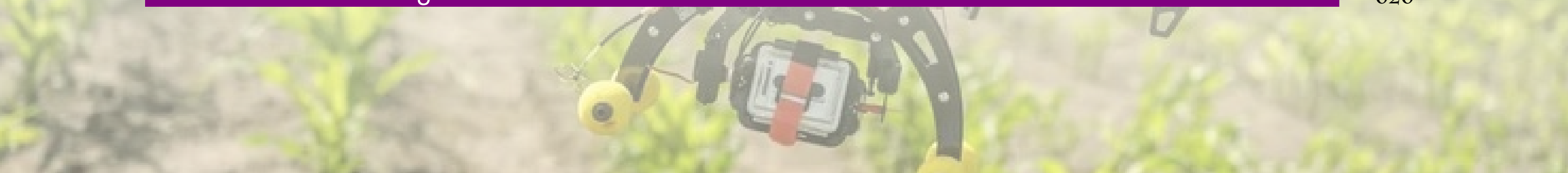
8. References

Barman, S., Bhattacharyya, R., Singh, C., Rathore, A. C., Singhal, V., Biswas, D. R., Moussa, I. M., 2025. Long-term agroforestry enhances soil organic carbon pools and deep soil carbon sequestration in the Indian Himalayas. Frontiers in Environmental Science 13, 1568564.

Chaudhary, V.P., Sawant, C.P., Gupta, A., Gautam, R., Khadatkar, A., Magar, A.P., Chaudhary, R., 2025. Long-term zero tillage with residue retention boosts yield, enhances energy efficiency, and mitigates greenhouse gas emissions in the western Indo-Gangetic rice–wheat systems. Frontiers in Sustainable Food Systems 9, 1672467.

Das, T.K., Nath, C.P., Bhattacharyya, R., Bandyopadhyay, K., Sudhishri, S., Bhatia, A., Chaudhari, S.K., 2025. Conservation agriculture in cotton–wheat system of the northwestern Indo-Gangetic Plains: yield sustainability, water productivity, carbon stocks and greenhouse gases emissions. International Journal of Plant Production 19(1), 31–45.

Dash, A.K., Meena, M.C., Das, S., Dey, A., Sangwan,



S., Bana, R.S., Mattar, M.A., 2025. Long-term conservation agriculture to enhance soil properties and quality in rice–wheat cropping system. Scientific Reports 15(1), 28393.

Goldman Sachs, 2016. Precision farming: Cheating Malthus with digital agriculture. Profiles in Innovation. The Goldman Sachs Group. https://www.gspublishing.com/content/research/en/reports/2016/07/13/6e4fa167-c7ad-4faf-81de-bfc6acf6c81f.pdf Accessed in March 2026.

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1 Accessed in December 2025.

Kumar, A., Malik, M.S., Shabnam, S., Kumar, R., Karmakar, S., Das, S.S., Kumar, J., 2024. Carbon sequestration and credit potential of gamhar (*Gmelina arborea* Roxb.) based agroforestry system for zero carbon emission of India. Scientific Reports 14(1), 4828.

Kumara, K., Birthal, P.S., Meena, D.C., Kumar, A., 2026. Unravelling trade-offs and synergies of direct-seeded rice in Indian agriculture: A meta-analysis. European Journal of Agronomy 173, 127897.

Pott, C.A., Conrado, P.M., Rampim, L., Umburanas, R.C., Conrado, A.M.C., Outeiro, V.H., Muller, M.M.L., 2023. Mixture of winter cover crops improves soil physical properties under no-tillage system in a subtropical environment. Soil and Tillage Research 234, 105854.