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Review

Sustainable Approaches to Net Zero Emission in Agriculture

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Abstract

Agriculture plays a crucial role in climate change, both as a significant contributor to greenhouse gas (GHGs) emissions and as a vulnerable sector suffering from climate impacts such as unpredictable weather patterns, prolonged droughts, and degraded soil health. Approximately 21% of all anthropogenic GHG emissions originate from farming and land-use changes, including deforestation. The primary sources include methane emissions from livestock and rice cultivation, nitrous oxide from synthetic fertilizers and carbon dioxide from fossil fuel consumption and deforestation activities. To address these challenges, agriculture must transition toward climate-smart and resilient practices. This transformation requires a three-pronged approach reducing on-farm emissions, enhancing carbon sequestration in soils and biomass and adopting renewable energy sources. Sustainable practices including conservation agriculture, agroforestry systems, organic soil amendments, precision agriculture technologies and smart farming tools demonstrate significant potential to mitigate emissions while simultaneously improving crop productivity and environmental sustainability. These integrated approaches offer a pathway for agriculture to evolve from a climate problem into part of the solution, ensuring food security while contributing to global climate mitigation efforts.

Keywords: Climate change, Greenhouse gas emissions, Climate-smart agriculture, Carbon sequestration and Sustainable farming practices.

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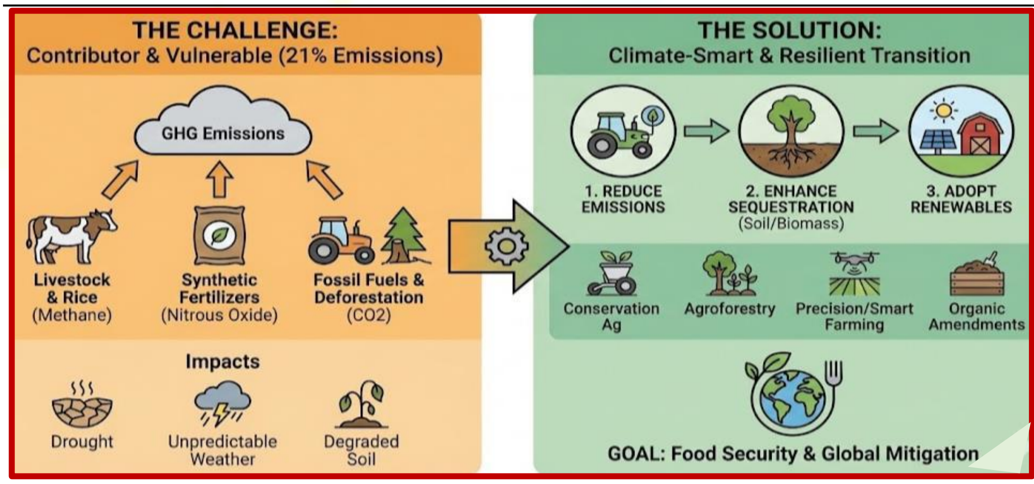

Fig. 1 The Dual Role of Agriculture in a Changing Climate

Introduction

Agriculture, forestry and land use (AFOLU) account for roughly a quarter of global greenhouse gases. Achieving net zero emissions in agriculture means balancing any remaining emissions with equal or greater removals (for example, by soils or biomass). In practice, this requires slashing on-farm emissions as much as possible and offsetting the rest via carbon sinks. Today agriculture is a major GHG source. FAO estimates AFOLU emits roughly 21% of global GHG (about as much as electricity generation) [1&2]. The sector produces CO_2 (from land clearing and machinery), nitrous oxide (from fertilizers) and methane (from rice paddies and livestock). At the same time, farming is highly vulnerable to climate change higher temperatures, erratic rainfall and extreme events (droughts, floods, heat waves) already reduce crop yields worldwide. Smallholder farmers who produce about one-third of the world's food are especially at risk from changing weather and pests. In this context, transforming farming to be climate smart is urgent we must reduce farm emissions and bolster the system's resilience simultaneously.
Net zero in agriculture thus means that by mid-century farms and forests remove as much carbon and other GHGs as they emit. This cannot happen on every farm but needs to occur at the sector level. Achieving that requires sweeping change. Fortunately, agriculture also has tools to become a net carbon sink: healthy soil and trees can store huge amounts of carbon.

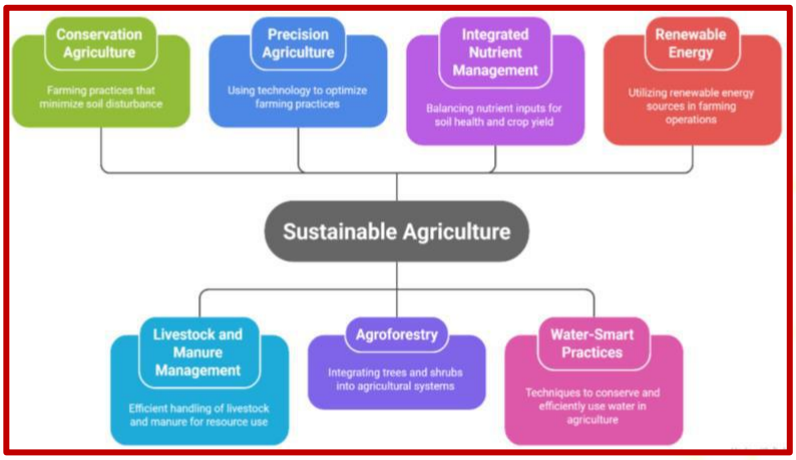

Fig. 2 Strategies for Sustainable Agriculture

Fig. 3 Key Climate-Smart Agricultural Practices for Achieving Net-Zero Emissions

Conservation Agriculture

Conservation agriculture (CA) is a cornerstone of low-emissions farming. It promotes minimal soil disturbance, permanent soil cover and crop diversification. Key practices include no-till (or minimal tillage), cover cropping, crop rotation and residue retention.
Together, these practices protect the soil and build organic matter, which slows or even reverses carbon loss. For example, leaving crop residues on the field or planting winter cover crops feeds soil microbes and locks carbon in the ground. Reduced tillage also avoids the CO_2 "burst" that comes from turning over soil.

Agroforestry Systems

Agroforestry (deliberately combining trees with crops or livestock) is another high-impact climate-smart approach. Trees on farms sequester carbon above and below ground, provide shade and enrich biodiversity. Estimates suggest agroforestry could be one of the single largest climate mitigation actions in agriculture, comparable to large-scale reforestation. Integrating native trees (fruit trees, timber species or nitrogen-fixing shrubs) into fields or pastures adds massive carbon storage capacity.

Moreover, agroforestry delivers multiple co-benefits. Trees create habitat for pollinators and wildlife, improve soil fertility through litterfall and nitrogen fixation and buffer crops and livestock from heat and floods. The Nature Conservancy reports that agroforestry can improve crop yields and diversify incomes, enhance climate resilience, create habitat for biodiversity and protect against extreme weather.

Integrated Nutrient Management (INM)

Applying fertilizer more intelligently is vital to cutting GHGs. Integrated Nutrient Management (INM) means using the best mix of chemical fertilizers, organic manures (e.g. compost, farmyard manure), crop residues, green manures and biofertilizers (like nitrogen-fixing bacteria or mycorrhizae). Instead of relying solely on synthetic fertilizers (which can drive high nitrous oxide losses), INM matches nutrient supply to plant needs timing and quantities are carefully controlled and supplements with organic inputs to feed soil biology.

In practice, INM might look like this: applying farmyard manure and crop residues with only half the usual synthetic nitrogen, plus inoculating seeds with rhizobia for a legume cover. The organic inputs slowly release N and improve soil structure, while the remaining inorganic fertilizer prevents yield gaps. Adding biochar or compost also locks some carbon in the soil.

Over time, INM increases soil aggregate stability, porosity and organic carbon. Crucially, it reduces nitrous oxide emissions for example precise fertilizer placement (deep-banding urea with N inhibitors) means less nitrogen is wasted as N_2O or lost to leaching.

Precision Agriculture

Modern technology has made farming more precise and efficient, directly reducing waste and emissions. Precision agriculture employs GPS-guided machinery, drones, soil and plant sensors and data analytics to deliver water, fertilizer and pesticides exactly where they're needed. For instance, drones can scan fields to identify nutrient deficiencies or pest hotspots; soil moisture sensors can activate irrigation only in dry zones; and AI-driven controllers can adjust fertilizer rates row by row [3]. The benefits are well documented. Farmers using precision systems often achieve equal or better yields while using less fertilizer, pesticide, fuel and water.

For example:

Variable-rate fertilizer applicators guided by soil maps can cut overall nitrogen use by 20-30% without a yield penalty.

Precision irrigation systems (drip lines with moisture sensors or automated valves) can save 30-50% of water (and the pumping energy) compared to flood irrigation.

On livestock farms, automated feeders dispense the right ration to each animal, minimizing feed waste and associated methane emissions.

Water-Smart Practices

Efficient water management is both a climate mitigation and adaptation strategy [4]. Irrigated crops can emit methane (notably from flooded rice paddies) or nitrous oxide and pumping water often uses fossil fuels. Switching irrigation methods can cut these emissions significantly.

One well-established practice is Alternate Wetting and Drying (AWD) in rice. Rather than keeping paddies continuously flooded (which causes methane via anaerobic decomposition), AWD allows the field to dry intermittently. AWD substantially reduces methane emissions from rice trials by IRRI and others typically find 30-50% lower CH_4 per hectare with little or no yield loss when fields are periodically drained.

Water-smart agriculture also includes

Using drip or sprinkler irrigation to avoid overwatering, harvesting rainwater to buffer droughts and scheduling irrigation with weather forecasts.

Growing aerobic (non-flooded) rice varieties combined with AWD, which can cut methane emissions by up to ~70%.

In vineyards, using moisture sensors to irrigate only under true water stress, saving both water and pumping energy.

Generally reducing irrigation volume through efficient delivery this saves diesel or electricity and directly lowers CO_2 emissions.

Key renewable solutions include:

Biogas: Anaerobic digesters convert manure and crop residues into methane-rich biogas for cooking or electricity. Capturing this methane (that would otherwise emit from manure heaps) directly reduces methane emissions, while replacing coal or gas for energy further cuts GHGs. The leftover digestate is a nutrient-rich fertilizer, completing the nutrient loop. (For example, India's MNRE "gobar gas" scheme supports on-farm digesters each plant cuts fuelwood or LPG use and slashes greenhouse gases).

Biomass and waste: Crop residues (like rice husks) can power biomass co-generation plants, turning waste into energy and bio-fertilizers. Industrial byproducts can also produce bio-fertilizers or biofuels, reducing fossil input.

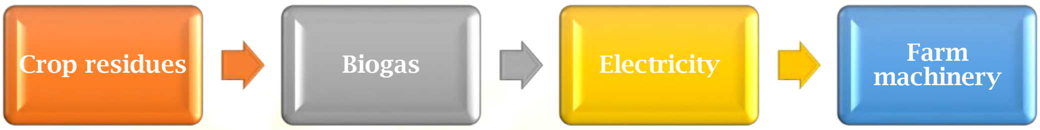

Fig. 4 Circular Bioeconomy Model for Net-Zero Agriculture

Wind and agrivoltaics: Even small wind turbines on farms can run pumps or equipment with zero emissions. In wealthier countries, "agrivoltaics" planting solar panels over crop rows shows promise by generating power while sometimes improving the crop microclimate [5&6].

Improved Livestock and Manure Management

Livestock contribute significantly to agriculture's GHGs, mainly via enteric methane (from cattle, sheep, goats) and manure emissions. Smart animal and manure management can cut these emissions.

On the enteric side, improving feed quality and digestibility means animals produce less methane per unit of product. For example, diets higher in energy and properly balanced protein can raise milk yield per cow reducing methane per liter of milk. Boosting overall production efficiency is one of the "fastest ways to reduce methane globally," since more feed energy goes into meat or milk rather than CH_4. Several countries reduce dairy methane through selective breeding (more productive cows) and dietary tweaks. New feed additives (like certain oils, tannins or the red seaweed *Asparagopsis*) can inhibit methane-producing microbes in ruminant guts trials have shown up to 30-80% CH_4 reductions depending on the additive. These technologies are just reaching the market, but their impact could be enormous: some tests with *Asparagopsis* even cut enteric CH_4 by ~99%.

Fig. 5 Circular Bioeconomy Model for Net-Zero Agriculture

Manure management: The focus is on containing or converting methane and nitrous oxide from manure. Anaerobic digesters (biogas systems) prevent methane leaks: covered digesters emit far less CH_4 than open lagoons because the gas is captured and used. On a medium-sized dairy farm, even a small digester can halve net methane output (especially if the biogas replaces diesel or grid power) [7]. The digestate is a stabilized fertilizer, completing the nutrient cycle.

Composting and solid storage: Aerobic composting of manure (pile or bay) reduces methane (since oxygen is present), though it may emit more N_2O than lagoons. Quickly separating solids and regularly spreading manure on fields (instead of storing it in anaerobic tanks) can dramatically cut methane emissions. Practices like acidifying slurry or covering storage tanks also reduce CH_4. Each method has trade-offs, but the goal is to avoid long anaerobic storage that churns out methane [8].

Grazing and animal efficiency: Properly managed rotational grazing (with recovery periods) enhances grass growth and sequesters more carbon in pasture soils. Breeding or feeding strategies that raise average daily gains per animal automatically reduce the methane emitted per unit of meat or milk [9].

Table-1: Impact of Sustainable Practices on Emission Reduction

Practice	GHGs Reduced	Additional Benefits
Conservation Tillage	CO_2	Soil carbon storage, moisture retention
Integrated Nutrient Management	N_2O	Better nutrient use, yield stability
Agroforestry	CO_2	Carbon sequestration, biodiversity
Organic Amendments	N_2O, CO_2	Soil health, reduced chemical input

Conclusion

Moving agriculture towards net-zero emissions is not just important for fighting climate change it also helps protect farmers' incomes, improves soil and crop health and ensures future food security. Sustainable methods like conservation tillage, integrated nutrient management, agroforestry and using renewable energy can lower carbon emissions while boosting productivity. New technologies such as precision farming, climate-smart tools and carbon tracking systems help farmers use resources more efficiently and make better decisions. But to make this shift successful, strong support is needed through good policies, climate funding, training programs and active participation of farmers and communities. The transition must focus on farmers' needs and combine environmental care with profitable farming. By making sustainability a part of everyday agriculture, we can turn farming into a key solution for climate change and build a better, more secure future for all.

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