Available online at www.agrifarming.org

DOI: http://dx.doi.org/10.18782/2582-7146.337

ISSN: 2582 – 7146

Curr. Rese. Agri. Far. (2021) *2*(5), 13-23

Current Research in Agriculture and Farming

Review Article

Peer-Reviewed, Refereed, Open Access Journal

Current Advances in Climate-Smart Agriculture: Strategies for Sustainable Crop Production

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Received: 20.07.2021 | Revised: 28.08.2021 | Accepted: 13.09.2021

ABSTRACT

Climate change is undermining crop productivity, water availability and soil health, threatening global food security. Climate-Smart Agriculture (CSA), introduced by the Food and Agriculture Organization in 2010, is an integrative approach that pursues three simultaneous objectives: sustainably increasing productivity and incomes, adapting and building resilience to climate change, and reducing or removing greenhouse gas (GHG) emissions where possible. It discusses core CSA strategies including conservation agriculture, agroforestry, improved crop varieties, integrated soil-fertility and pest management, water-smart practices and digital agriculture, and highlights the enablers, barriers and policy needs shaping their adoption. Evidence indicates that context-specific CSA portfolios can raise yields, strengthen resilience and lower emission intensity, provided institutional, financial and knowledge constraints are addressed.

Keywords: *Climate-smart agriculture; sustainable crop production; conservation agriculture; agroforestry; climate resilience.*

INTRODUCTION

Agriculture stands at the crossroads of the twenty-first century food and climate challenge. It must feed a projected 9.7 billion people by 2050, while simultaneously coping with rising temperatures, altered rainfall patterns, more frequent droughts and floods, salinisation, and new pest and disease pressures (FAO, 2018; IPCC, 2019). At the same time, the sector is itself a major contributor to climate change. According to FAO (2021), global agrifood-system greenhouse gas (GHG) emissions reached about 16 Gt CO_2-equivalent in 2020, accounting for roughly 31% of total anthropogenic emissions, with crop and livestock activities within the farm gate contributing the largest single share. The IPCC (2019) Special Report on Climate Change and Land similarly attributes 21–37% of global GHG emissions to the food system when supply chains are included.

Cite this article: Patel, R., & Bhargava, R. (2021). Current Advances in Climate-Smart Agriculture: Strategies for Sustainable Crop Production, *Curr. Rese. Agri. Far.* *2*(5), 13-23. doi: http://dx.doi.org/10.18782/2582-7146.337

This dual role, as victim and driver of climate change, underscores the urgent need for a transformative approach to crop production. The concept of Climate-Smart Agriculture (CSA) was first introduced by the FAO at the 2010 Hague Conference on Agriculture, Food Security and Climate Change. FAO (2013) defined CSA as "agriculture that sustainably increases productivity, resilience (adaptation), reduces or removes GHGs (mitigation), and enhances the achievement of national food security and development goals". Lipper et al. (2014) further formalised the three interlinked pillars of CSA — productivity, adaptation and mitigation — and emphasised that trade-offs among them must be managed through context-specific packages of technologies, policies and investments. Since then, CSA has become a central organising framework for climate action in agriculture, endorsed under the United Nations Framework Convention on Climate Change (UNFCCC) Koronivia Joint Work on Agriculture and reflected in the Nationally Determined Contributions (NDCs) of more than 100 countries (Richards et al., 2019).

CSA is not a fixed set of practices; rather, it is a decision framework that identifies which combinations of practices, institutions and enabling conditions best deliver the three pillars under specific agro-ecological and socio-economic settings (FAO, 2013; Lipper & Zilberman, 2018). At the field level, CSA draws on well-established sustainability approaches such as conservation agriculture, agroforestry, integrated soil-fertility and pest management, water-smart practices, improved genetics and, more recently, digital and precision agriculture (Aryal et al., 2020; Zerssa et al., 2021). At the landscape and policy levels, it links these on-farm practices with early-warning systems, weather-index insurance, extension services, carbon finance and climate-informed value chains (Khatri-Chhetri et al., 2017; Thornton et al., 2018).

2. Conceptual Foundations and Pillars of CSA

Climate-Smart Agriculture integrates the economic, social and environmental dimensions of sustainable development by simultaneously addressing food security and climate challenges (FAO, 2013). FAO (2013) and Lipper et al. (2014) describe CSA as resting on three interconnected pillars: (i) sustainably increasing agricultural productivity and incomes, (ii) adapting and building resilience of farming systems to climate change, and (iii) reducing and/or removing GHG emissions where possible. These pillars are visualised in Figure 1, together with representative practices and their combined contribution to food security and sustainable development.

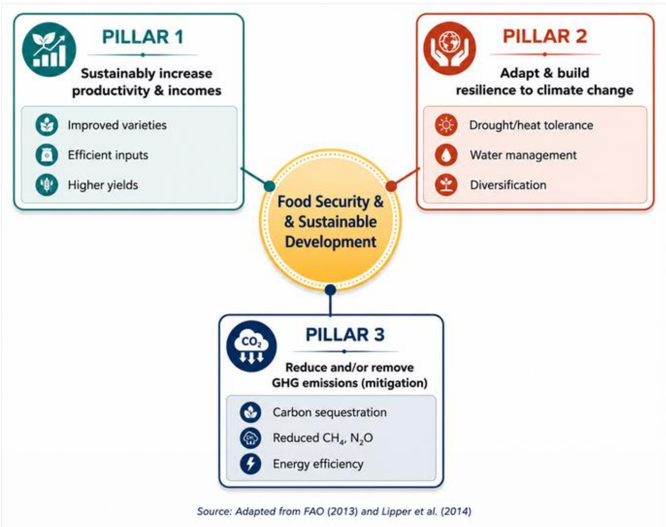

Figure1. The three interlinked pillars of Climate-Smart Agriculture (adapted from FAO, 2013; Lipper et al., 2014).

The productivity pillar addresses the persistent challenge of low and stagnant yields in many developing regions, where population growth continues to outpace agricultural output (FAO, 2018). It emphasises efficient use of inputs, improved cultivars, precision management and diversification. The adaptation pillar seeks to reduce vulnerability to climate risks by combining agronomic, genetic, institutional and financial measures such as drought-tolerant crops, soil moisture conservation, weather-index insurance and crop-livestock integration (Aryal et al., 2020; Thornton et al., 2018). The mitigation pillar targets the direct and indirect emissions from crop production — nitrous oxide from fertiliser use, methane from paddy rice, and carbon losses from tillage and land-use change — and enhances carbon sequestration in soils and biomass (Smith et al., 2014; Paustian et al., 2016).

FAO (2013) further identified five implementation "entry points" for operationalising CSA: expanding the evidence base, supporting enabling policy frameworks, strengthening national and local institutions, enhancing financing options, and implementing practices at field level. Neufeldt et al. (2013) cautioned, however, that CSA must remain grounded in scientific evidence and social equity, avoiding the risk of "climate-washing" by ensuring that labelled practices genuinely deliver on all three pillars. The interpretation of CSA as a decision framework rather than a fixed technology package (Lipper et al., 2014; Rosenstock et al., 2016) is therefore essential for its use in diverse crop production systems.

3. Agriculture and the Climate Challenge

Understanding the magnitude of agricultural emissions is a precondition for designing effective CSA strategies. Between 2000 and 2020, absolute GHG emissions from global agrifood systems increased from about 14.7 to 16.0 Gt CO_2-equivalent (FAO, 2021). However, because emissions from energy and industry grew faster, agrifood systems' share of total anthropogenic emissions declined from 38% to 31% over the same period (FAO, 2021; Crippa et al., 2021). Figure 2 illustrates this trajectory, showing the growth in absolute emissions alongside the declining relative share.

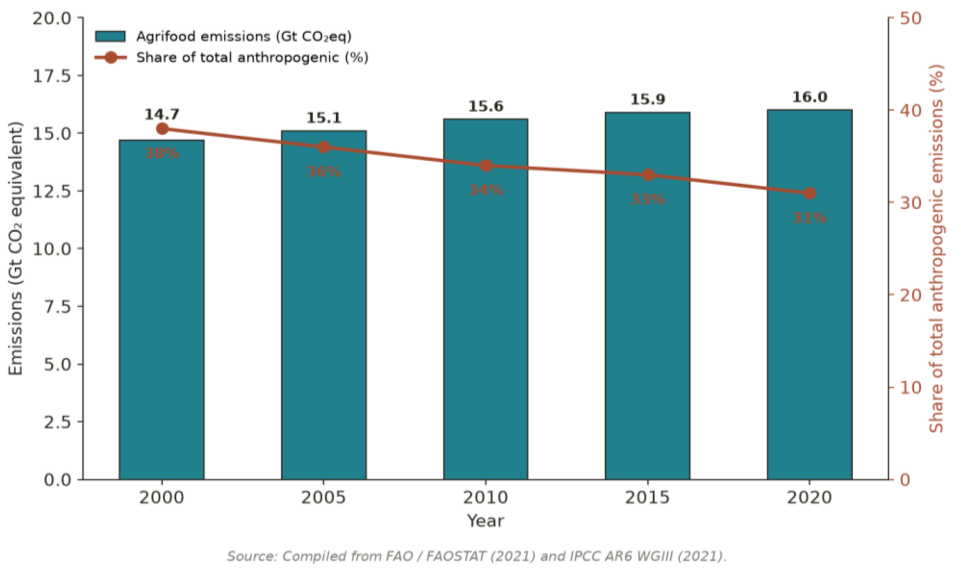

Figure 2. Global agrifood system GHG emissions and their share of total anthropogenic emissions, 2000–2020 (compiled from FAO, 2021 and IPCC, 2021).

Within agriculture, methane (CH_4) from enteric fermentation, manure and rice cultivation and nitrous oxide (N_2O) from synthetic fertilisers and manure account for the largest share of non-CO_2 emissions. IPCC (2019) reports that agriculture is responsible for approximately 42% of anthropogenic CH_4 and 75% of N_2O emissions. In addition, land-use change driven by cropland expansion contributes to carbon losses, biodiversity decline and soil degradation. Simultaneously, climate change threatens the productivity base of agriculture. Global-scale meta-analyses suggest that, without adaptation, yields of major cereals such as wheat, rice and maize are likely to decline by 3–7% for every 1°C rise in mean temperature, with disproportionate impacts on tropical smallholder systems (Zhao et al., 2017; IPCC, 2019). These findings reinforce the argument that adaptation and mitigation in cropping systems must be pursued together, precisely the space that CSA is designed to occupy.

4. Current Advances in CSA Strategies for Crop Production

A wide portfolio of CSA practices has emerged over the past decade, spanning agronomic, genetic, ecological and digital innovations. Figure 3 summarises the most commonly reported CSA practices and their approximate adoption levels among surveyed smallholder farmers, based on syntheses reported in Kassam et al. (2019), Aryal et al. (2020) and Zerssa et al. (2021).

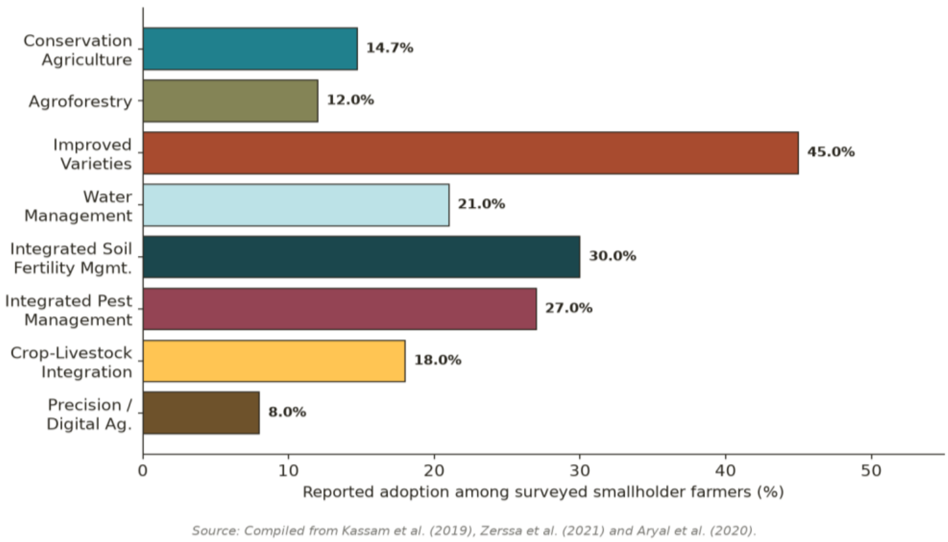

Figure 3. Common Climate-Smart Agriculture practices and reported adoption levels among smallholder farmers (compiled from Kassam et al., 2019; Zerssa et al., 2021; Aryal et al., 2020).

4.1 Conservation Agriculture

Conservation Agriculture (CA) is built on three interlinked principles: minimum mechanical soil disturbance, permanent soil cover through crop residues or cover crops, and diversified crop rotations (Kassam et al., 2019). Kassam et al. (2019) estimated that CA was practised on around 205 million hectares globally in 2018/19, corresponding to about 14.7% of total global cropland. CA improves soil structure, water infiltration, biological activity and organic carbon stocks. Powlson et al. (2016) reported that CA can sequester 0.3–0.6 t C ha^{-1} yr^{-1} under favourable conditions, while also reducing energy use and fuel-related emissions. Nevertheless, Pittelkow et al. (2015) cautioned that yield outcomes vary widely; no-tillage without residue retention and rotation may reduce yields in the short term. Site-specific integration of all three CA principles, combined with improved varieties and integrated nutrient management, is therefore essential (Corbeels et al., 2020).

4.2 Agroforestry

Agroforestry — the intentional integration of trees with crops and/or livestock — delivers strong contributions to all three CSA pillars. Trees stabilise microclimates, moderate temperature and humidity, add organic matter, and provide additional income streams from fruit, fodder and timber (Nair, 2014; Mbow et al., 2014). Zomer et al. (2016) estimated that agroforestry systems already cover more than one billion hectares worldwide and sequester substantial amounts of carbon in above- and below-ground biomass. Species such as Faidherbia albida in the Sahel and evergreen shrubs in the Ethiopian highlands are documented to raise maize and sorghum yields by 30–200% relative to sole-cropped controls (Garrity et al., 2010). Agroforestry also enhances biodiversity and buffers farmers against price and weather shocks, aligning strongly with the resilience pillar of CSA.

4.3 Climate-Resilient Crop Varieties

Advances in plant breeding and genomics have delivered a growing pipeline of climate-resilient varieties. Stress-tolerant maize, submergence-tolerant “Scuba” rice, drought-tolerant beans, and heat-tolerant wheat have collectively benefited millions of smallholders across Africa and Asia (Cairns et al., 2013; Ismail et al., 2013; Fisher et al., 2015). Marker-assisted selection, genomic prediction and, more recently, CRISPR-based genome editing are accelerating the introgression of stress-tolerance traits and reducing breeding cycles (Varshney et al., 2021). Mickelbart et al. (2015) further emphasised the strategic role of stress-adaptive alleles in future breeding pipelines. However, adoption depends on functional seed systems, farmer awareness and complementary agronomy; Fisher et al. (2015) found that adoption of drought-tolerant maize in eastern and southern Africa ranged widely, from below 10% in some countries to over 60% where seed distribution and extension were strong.

4.4 Integrated Soil Fertility and Water Management

Integrated Soil Fertility Management (ISFM) combines judicious use of mineral fertilisers with organic inputs, improved germplasm and adapted agronomic practices (Vanlauwe et al., 2015). ISFM increases nutrient-use efficiency, reduces N_2O emissions from over-fertilisation, and rebuilds soil organic matter. Complementary water-smart practices include laser land levelling, alternate wetting and drying (AWD) in paddy rice, drip and micro-sprinkler irrigation, rainwater harvesting, and moisture-conserving mulches (Jat et al., 2016; Aryal et al., 2020). Field studies of AWD in South and Southeast Asia have documented water savings of 15–30% and methane reductions of 30–70% without yield penalties (Lampayan et al., 2015). Laser land levelling in the Indo-Gangetic Plains has been shown to reduce irrigation water use by up to 25% and diesel consumption by 20% (Aryal et al., 2015). Such practices exemplify the productivity-adaptation-mitigation synergies that define CSA.

4.5 Integrated Pest Management and Crop Diversification

Climate change is altering pest and disease dynamics, favouring range expansion of invasive species and new outbreaks (Deutsch et al., 2018). Integrated Pest Management (IPM) combines biological control, host-plant resistance, cultural practices and judicious pesticide use to protect crops with minimal environmental cost (Pretty & Bharucha, 2015). Diversification through intercropping, cover cropping, crop rotations and mixed farming reduces pest pressure, buffers against yield failure and enhances nutrient cycling (Lin, 2011; Beillouin et al., 2021). Beillouin et al. (2021) synthesised over 5 000 experiments and showed that diversified systems maintained productivity and improved biodiversity, soil quality and pest regulation compared with monocultures. These strategies form a core part of ecologically-based CSA portfolios, particularly for smallholders with limited access to external inputs.

4.6 Digital and Precision Agriculture

The maturation of digital technologies has opened new frontiers for CSA. Remote sensing, geographic information systems, unmanned aerial vehicles, Internet-of-Things sensors and mobile advisory platforms now support site-specific management of water, nutrients and pests (Balafoutis et al., 2017;

Basso & Antle, 2020). Weather-index insurance and mobile-based climate advisories — such as the Modernising Extension and Advisory Services (MEAS) and Climate Information Services for Farmers in Africa — have improved farmers' capacity to make climate-informed decisions (Vaughan et al., 2017; Ouedraogo et al., 2018). Precision-fertiliser tools such as GreenSeeker and Nutrient Expert have reduced fertiliser use by 10–25% and cut N_2O emissions while maintaining yields in South Asia (Sapkota et al., 2019). Digital CSA remains constrained by infrastructure, data access and equity concerns, but it represents an increasingly important pathway to scale.

5. Enablers, Barriers and Policy Dimensions

Despite a rich and growing evidence base, adoption of CSA practices among smallholders remains uneven. Systematic reviews consistently identify a set of institutional, socio-economic and knowledge-related factors that determine whether CSA practices are taken up and sustained (Khatri-Chhetri et al., 2017; Aryal et al., 2020; Zerssa et al., 2021). Figure 4 summarises the enablers and barriers reported most frequently across these reviews.

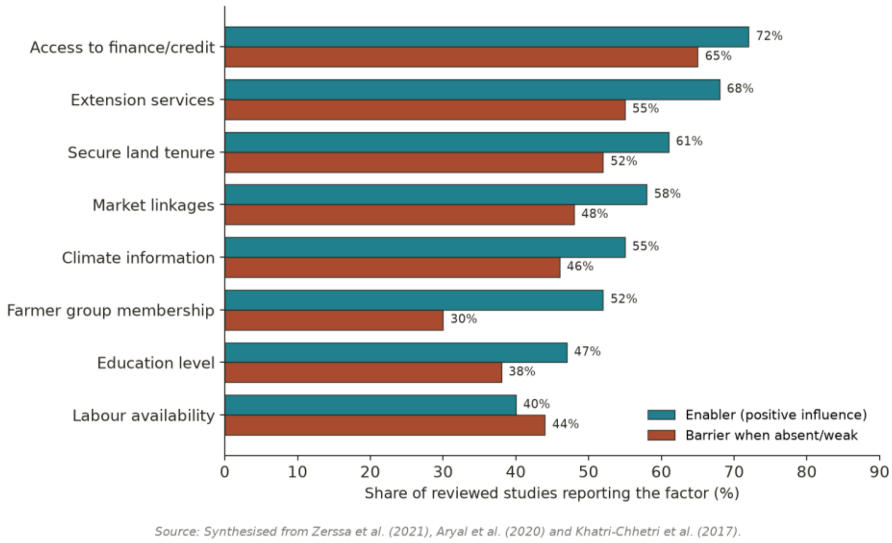

Figure 4. Enablers and barriers to adoption of Climate-Smart Agriculture practices (synthesised from Zerssa et al., 2021; Aryal et al., 2020; Khatri-Chhetri et al., 2017).

Access to finance and credit consistently emerges as the most important enabler, since many CSA practices require upfront investment in equipment, inputs or trees (Khatri-Chhetri et al., 2017). Effective extension services and functional farmer organisations also strongly influence adoption, by reducing information asymmetries and facilitating peer learning (Ndiritu et al., 2014). Secure land tenure encourages long-horizon investments such as agroforestry, terracing and organic-matter build-up (Deininger & Feder, 2001). Market linkages that reward sustainably produced grain, pulses and horticultural crops raise the economic returns to CSA. Access to climate information, in the form of seasonal forecasts, downscaled advisories and early warnings, enables farmers to align planting, input use and marketing decisions with expected conditions (Vaughan et al., 2017; Ouedraogo et al., 2018).

Persistent barriers include weak extension coverage, gender-based inequalities in access to resources and information (Perez et al., 2015), unfavourable price and subsidy regimes, and short-term risk aversion driven by poverty and food insecurity. Trade-offs among the three CSA pillars are also increasingly recognised. For instance, expanding synthetic-fertiliser use to close yield gaps in sub-Saharan Africa may improve food security but raise emissions if not paired with precision nutrient management (Sapkota et al., 2019). Similarly, some conservation practices may reduce short-run yields, requiring transitional support (Pittelkow et al., 2015). CSA planning therefore needs to explicitly assess synergies and trade-offs, ideally using participatory prioritisation tools such as the CSA-Rapid Appraisal (CSA-RA), Climate-Smart Village approaches and CGIAR CCAFS decision-support tools (Aggarwal et al., 2018; Rosenstock et al., 2016).

At the policy level, mainstreaming CSA into national agricultural strategies, NDCs and public-investment plans is essential for scaling. Richards et al. (2019) documented that 89% of NDCs submitted under the Paris Agreement prioritised adaptation in agriculture and 80% committed to mitigation actions in the sector, providing strong policy anchoring for CSA. Climate finance instruments such as the Green Climate Fund, Adaptation Fund and results-based carbon payments have begun to channel resources to CSA at scale, although flows remain small relative to needs (FAO & UNDP, 2020). Payments for ecosystem services, insurance subsidies, input smart-subsidies, and public procurement standards can further align private incentives with climate-smart choices (Lipper & Zilberman, 2018).

CONCLUSION

Climate change is redefining the conditions under which crops are grown, threatening food security and rural livelihoods, while agriculture itself is a major source of greenhouse gases. Climate-Smart Agriculture, as formalised by FAO (2013) and Lipper et al. (2014), provides a coherent framework for reconciling these tensions through simultaneous pursuit of productivity, adaptation and mitigation. This review has shown that a rich portfolio of CSA strategies is available for sustainable crop production, spanning conservation agriculture, agroforestry, climate-resilient varieties, integrated soil-fertility and water management, integrated pest management, diversification and rapidly maturing digital tools. Evidence up to 2021 indicates that, when combined in context-specific ways, these practices can raise yields, improve resilience to climate variability, and reduce emission intensity per unit of product. Meta-analyses further suggest that bundled CSA interventions frequently outperform single-practice adoption in terms of both productivity and resilience gains (Rosenstock et al., 2016; Beillouin et al., 2021), reinforcing the value of a portfolio approach.

The transition to climate-smart crop production is fundamentally a knowledge- and institution-intensive process. It requires reliable weather and climate information, robust extension systems, functional seed and input markets, secure land and water rights, and financial products that reduce the private risk of adoption. It also requires social and gender inclusion, so that women farmers, youth and marginal communities — who often manage the crops most exposed to climate risk — can access the same technologies, credit and information as better-resourced farmers (Perez et al., 2015; Ndiritu et al., 2014). Landscape-level coordination is equally important, since watershed health, pollination services and pest dynamics extend beyond individual fields (Aggarwal et al., 2018).

Nonetheless, adoption remains uneven and constrained by financial, institutional, informational and cultural barriers. Realising the full potential of CSA for sustainable crop production requires a coordinated effort across scales: participatory identification of context-appropriate practice bundles at the farm and landscape level; strengthened extension, climate information and insurance services; targeted finance and de-risking instruments; secure land and water rights; and mainstreaming of CSA into national agricultural, climate and food-security policies. Equity considerations — particularly regarding smallholders, women and youth — must be central to CSA design if the approach is to deliver genuinely sustainable outcomes. Future research priorities include better metrics and monitoring, systematic assessment of synergies and trade-offs, deeper integration of digital and genomic tools with agro-ecological principles, and stronger linkages between on-farm CSA and broader food-system transformation. Continued investment in long-term experiments, farmer-led innovation platforms and open data infrastructures will be critical to fill remaining evidence gaps, particularly for tropical smallholder systems where climate impacts are most acute (Thornton et al., 2018; Rosenstock et al., 2016). If these conditions are met, CSA can play a decisive role in achieving climate-resilient, low-emission and inclusive crop production consistent with the Sustainable Development Goals, and can help ensure that the twin objectives of feeding humanity and safeguarding the planet advance together rather than in opposition.

Acknowledgement:
I would like to sincerely thank my co-author for their support and kind gesture to complete this manuscript in time.

Funding: NIL.

Conflict of Interest:
There is no such evidence of conflict of interest.

Author Contribution:
All authors have participated in critically revising of the entire manuscript and approval of the final manuscript.

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