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# Climate change impact and relevance of Regenerative Agriculture to sustained crop yield, reduced pesticide load, sustained farmers livelihood and carbon mitigation

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**Abstract**

Climate change poses severe challenges to global agriculture, disrupting crop productivity, increasing chemical dependency, and threatening the livelihoods of small and marginal farmers. This paper examines the impact of climate change on agricultural systems and the potential of regenerative agriculture to sustain crop yields, reduce pesticide loads, support farmers' livelihoods, and mitigate carbon emissions. By integrating the Clean Food Net Zero (CFNZ) Program with Inhana Rational Farming (IRF) Technology and utilizing advanced composting methods such as Novcom Composting, the study demonstrates that regenerative practices can enhance soil health, boost crop productivity by up to 22%, and significantly reduce greenhouse gas emissions through improved nutrient cycling and carbon sequestration. Field evaluations from West Bengal, India, underscore how these interventions not only lower emissions from conventional practices but also transform agriculture into a viable carbon sink while promoting safe, pesticide-free produce. Overall, the findings reinforce that adopting a net zero regenerative agriculture model is a viable strategy for addressing the multifaceted impacts of climate change, ensuring food security, and elevating the socio-economic conditions of farming communities.

***Key words :*** *Novcom composting technology, IRF Technology, ACFA version 2.0, Agri-Net Zero model*

## Introduction

Climate change poses multifaceted challenges to modern agriculture, severely impacting crop productivity through altered weather patterns, increased frequency of extreme events, and shifts in pest and disease dynamics (Subedi et al, 2023). These climate-induced stresses not only lead to reduced crop yields but also escalate production costs, thereby exacerbating the difficulties associated with ensuring food and nutritional security (Tchonkouang et al, 2024). Moreover, the agricultural sector occupies a paradoxical role in the climate nexus—it both contributes to greenhouse gas emissions and suffers from the adverse effects of climate change (Gupta and Pathak, 2016). In countries like India, where more than 80% of the farming community comprises small and marginal farmers who are resource-poor and highly vulnerable to climatic shocks, the stakes are even higher (Mubashir and Bhat, 2021). These groups often face compounded risks, including financial instability and limited access to resilient technologies, making them disproportionately affected by the escalating costs and productivity losses due to climate variability.

Against this backdrop, regenerative agriculture has emerged as a promising paradigm aimed at sustaining crop yields while simultaneously reducing reliance on chemical inputs such as pesticides. This approach underscores the importance of managing both soil and plant health to not only restore the ecological balance but also enhance the resilience of agricultural systems. By aligning farming practices with ecosystem services, regenerative methods aim to improve soil fertility, bolster biodiversity, and enhance carbon sequestration, all while being socially acceptable, easily adoptable, economically viable, and replicable on a large scale. The integration of regenerative agriculture practices represents a critical pathway for mitigating the twin challenges of climate change and the systemic vulnerabilities of conventional agricultural systems (Lal, 2020). Its holistic framework offers a sustainable solution that addresses the immediate needs of crop productivity and farmer livelihoods, while also contributing to long-term environmental stability and climate mitigation efforts (Chepngeno et al, 2024).

In this context, Nadia Krishi Vigyan Kendra, BCKV, ICAR, located in West Bengal, India, has joined hand with Inhana Organic Research Foundation (IORF), India, to initiate a pesticide-free, safe, and sustainable cultivation system. This collaborative effort infuses the principles of regenerative farming by implementing the Inhana Rational Farming (IRF) Technology—a nature-harnessed, sustainable package that advocates for the integrated management of soil and plant health as critical components for enhancing crop sustainability, economic viability, and carbon mitigation. The initiative aims to establish a comprehensive agricultural production system that not only bolsters crop productivity and nutrient uptake efficiency but also significantly reduces pesticide loads, facilitates energy transitions, uplifts soil quality, and mitigates carbon emissions. Ultimately, the present study seeks to develop and validate a regenerative agriculture model that promotes livelihood sustenance and contributes to broader environmental benefits including carbon mitigation, thereby uplifting the overall socio-economic conditions of the farming community.

## Materials and method

### Study area

The study was done at the project site comprised five villages namely Satyapole, Bhabanipur, Panchkahaniya, Dhopagachi and Bansbona in the Haringhata block of Nadia district of West Bengal, India. The area belongs to hot, moist subhumid ecological sub region (15.1) (Sehgal, 1992). The climate of the study area is characterized by oppressively hot summer, high humidity and high rainfall during the monsoon.

### Concept of Clean Food Net Zero (CFNZ) program

The Clean Food Net Zero (CFNZ) Program is a transformative and holistic initiative designed to revolutionize agricultural practices while significantly reducing greenhouse gas emissions. Central to its approach is the implementation of Inhana Rational Farming (IRF) Technology—a nature-harnessed, sustainable package that integrates comprehensive soil and plant health management (Bera et al, 2023). By doing so, IRF Technology enhances crop sustainability, increases yields through improved photosynthetic efficiency, and provides a robust mechanism for carbon sequestration and emission mitigation. One of the program's core principles is that its strategies must be aligned with ecosystem services, economically viable, socially acceptable, easily adoptable, and scalable on a large scale. In addition to driving environmental benefits, the CFNZ Program is committed to ensuring that safe, nutritious, and affordable food is available for all. Equally important, it seeks to sustain and uplift the livelihoods of small and marginal resource-poor farmers by providing them with cost-effective, sustainable farming practices that can be readily implemented. Together, these integrated objectives not only fortify food security and public health but also empower farming communities, thereby contributing significantly to both climate resilience and inclusive economic development.

### Novcom composting technology

Novcom Composting Technology is an advanced bio-conversion process engineered to rapidly transform diverse biodegradable wastes—including agricultural byproducts and landfill residues—into nutrient-dense compost that is exceptionally rich in microorganisms (on the order of $10^{16}$ cfu per gram of moist compost). This technology distinguishes itself by achieving complete compost maturity in just 21 days, a notable improvement over conventional windrow methods, primarily due to its capacity to generate a substantially higher native microbial population within the compost heap. The accelerated microbial activity not only expedites the decomposition process but also enhances soil nutrient cycling and promotes vigorous plant growth (Seal et al, 2012). Moreover, the process meets five critical criteria—safety, speed, effectiveness, comprehensiveness, and economic viability—making it highly suitable for any biodegradation program. By optimizing these biological processes, Novcom Composting Technology significantly reduces greenhouse gas emissions, particularly methane, thereby mitigating the overall carbon footprint associated with organic waste management. This efficient, cost-effective, and environmentally friendly approach renders it a valuable tool in sustainable agriculture and climate change mitigation strategies (Bera et al, 2024).

### Inhana Rational Farming (IRF) Technology

Inhana Rational Farming (IRF)T Technology is a comprehensive, nature-harnessed approach to agriculture that integrates advanced soil and plant health management practices to transform conventional, chemical-intensive farming into a more sustainable, resilient, and climate-friendly system (Seal et al, 2017a). By leveraging the synergistic interactions of native soil microbes, nutrient cycling, and plant physiological processes, IRF Technology enhances nutrient uptake and photosynthetic efficiency, thereby improving crop yield and quality. Its holistic methodology not only bolsters economic viability and crop sustainability but also promotes carbon sequestration and reduces greenhouse gas emissions by lowering dependency on artificial inputs. Designed to be economically viable, socially acceptable, and easily scalable, IRF Technology offers an adaptable pathway for small and marginal resource-poor farmers, ultimately contributing to a safer food supply and more resilient agricultural ecosystems (Seal et al, 2017b).

### Analytical methodology for soil, compost, crop production, energetics and carbon footprint

Analytical measurements were performed across several components—compost, soil, crop productivity, energetics, and carbon footprint—to assess the impacts of the intervention. For compost quality, 20 samples from individual Novcom compost heaps made from different biodegradable waste viz agricultural farm waste, water hyacinth, poultry litter, vegetable market waste and cow dung were collected and analyzed for various parameters following the standard methodology of Seal et al. (2012), and a Compost Quality Index (CQI) was computed as described by Bera et al. (2013). Soil quality was assessed by collecting samples from the 0–30 cm depth both before the experiment and one year later; these were analyzed for physicochemical properties and fertility using conventional methods (Jackson, 1973), while microbial biomass carbon was estimated through the dichromate oxidation method (Vance et al., 1987) and soil respiration was quantified by chemically titrating trapped $CO_2$ and measuring fluorescein diacetate hydrolysis (Haney et al., 2008). Crop productivity was determined according to guidelines by Patrick (1999) and converted into coconut equivalent yield, leading to an estimation of total system productivity as per the methods of Ghosh et al. (2021) and Naveen Kumar et al. (2017). Energetic parameters—including energy use efficiency, energy productivity, specific energy, energy intensiveness, and net energy—were calculated following Banaeian et al. (2011). Finally, the carbon footprint was evaluated using the ACFA (version 1.0) carbon computing standard, developed by the Inhana Organization Research Foundation (IORF), ICAR-ATARI, Kolkata (Zone-V), and i-NoCarbon Limited (i-NC), UK, which integrates relevant IPCC guidelines with empirical research findings.

**Result and discussion**

**Analysis of Compost quality**

Novcom compost quality was evaluated across diverse substrates—including agri-farm waste, water hyacinth, banana stump, and poultry litter—revealing distinct physical, chemical, and biological properties. Moisture contents ranged from approximately 59% to 64%, while pH values remained near neutral (7.24–7.8), ensuring a favorable medium for microbial activity. Electrical conductivity was highest in the poultry litter compost (2.84 dS/m), indicating a greater concentration of soluble salts. Organic carbon percentages were notably high in the banana stump (28.2%) and water hyacinth (27.1%) composts, and the C/N ratios varied from 11.6:1 to 15.2:1, reflecting moderate maturity and balanced nutrient availability. Although total nitrogen levels were relatively consistent (1.79–2.09%), total phosphorus and potassium contents varied, with poultry litter compost exhibiting the highest phosphorus (1.24%) and banana stump the highest potassium (1.51%). Microbial assessments showed bacterial counts ranging from 23 × 10^16 to 40 × 10^16, with substrate-specific variations also observed in fungal and actinomycete populations, suggesting differences in decomposition dynamics. The $CO_2$ evolution rate, an indicator of microbial metabolic activity and compost stability, was markedly higher in poultry litter compost (4.61 mg $CO_2$–C/g OM/day) compared to the 2.13–2.39 mg $CO_2$–C/g OM/day observed in the other substrates. Bioassay results further demonstrated that composts derived from agri-farm waste, water hyacinth, and banana stump supported robust plant growth, as evidenced by seedling emergence rates between 107–113% and germination indices exceeding unity (1.09–1.12), while the poultry litter compost showed slightly diminished performance (93% seedling emergence and a germination index of 0.89), indicating minor phytotoxicity. Overall, these findings illustrate that Novcom composts, particularly those made from agri-farm waste, water hyacinth, and banana stump, possess favorable qualities for sustainable agricultural application, balancing nutrient enrichment with microbial vitality and minimal phytotoxic risk.

**Table 1 : Analysis of Novcom compost quality**

| Sl No | Quality parameters | On-Farm Novcom Compost Agri-farm waste | Water hyacinth | Banana stump | Poultry litter |
|---|---|---|---|---|---|
| 1 | Moisture (%) | 61.2 | 64.3 | 63.7 | 59/1 |
| 2 | $pH_{(water)}$ | 7.61 | 7.24 | 7.41 | 7.8 |
| 3 | EC (1 :5) dS/m | 1.91 | 2.64 | 1.93 | 2.84 |
| 4 | Organic carbon (%) | 22.2 | 27.1 | 28.2 | 23.1 |
| 5 | CMI[2] | 2.17 | 1.83 | 1.91 | 2.37 |
| 6 | Total nitrogen (%) | 1.91 | 2.09 | 1.79 | 1.89 |
| 7 | Total phosphorus (%) | 0.57 | 0.97 | 0.91 | 1.24 |
| 8 | Total potassium (%) | 1.04 | 1.11 | 1.51 | 1.17 |
| 9 | C/N ratio | 11.6:1 | 13.0: 1 | 15.2:1 | 12.2:1 |
| 10 | Total bacterial count[3] | $31 \times 10^{16}$ | $40 \times 10^{16}$ | $33 \times 10^{16}$ | $23 \times 10^{16}$ |
| 11 | Total fungal count[3] | $17 \times 10^{16}$ | $30 \times 10^{14}$ | $30 \times 10^{14}$ | $12 \times 10^{14}$ |
| 12 | Total actinomycetes[3] count | $12 \times 10^{16}$ | $17 \times 10^{14}$ | $21 \times 10^{14}$ | $9 \times 10^{14}$ |
| 13 | $CO_2$ evolution rate (mg$CO_2$–C/g OM/day) | 2.39 | 2.16 | 2.13 | 4.61 |
| 14 | Seedling emergence (% of control) | 108 | 113 | 107 | 93 |
| 15 | Root elongation (% of control) | 101 | 98 | 105 | 96 |
| 16 | Germination index (phytotoxicity bioassay) | 1.09 | 1.11 | 1.12 | 0.89 |

**Crop productivity under conventional farmers practice and CFNZ program**

In a comprehensive evaluation conducted over a cropping year, five major crop sequences were studied: CS 1 (Tomato–Cucumber–Coriander), CS 2 (Potato–Brinjal–Cauliflower), CS 3 (Potato–Okra–Cabbage), CS 4 (Brinjal–French bean–Spinach), and CS 5 (Pumpkin–Okra–Cabbage). Notably, the Potato–Brinjal–Cauliflower sequence (CS 2) demonstrated the highest productivity, yielding 52,125 kg/ha under conventional farmer practices (CFP) and increasing to 92,775 kg/ha under the Clean Food Net Zero (CFNZ) program. This was followed by the Potato–Okra–Cabbage sequence (CS 3), which achieved yields of 66,937.5 kg/ha under CFP and 82,125 kg/ha under CFNZ. On average, the CFNZ program led to a 22% increase in crop yields compared to conventional practices. The observed yield improvements are scientifically attributed to the adoption of enhanced soil and plant health management practices, particularly through the integration of Inhana Rational Farming (IRF) Technology. This technology promotes a synergistic soil–plant interaction by boosting microbial biomass, nutrient cycling, and overall resource use efficiency, thereby enhancing photosynthetic activity and crop growth. Moreover, the methodological framework of the CFNZ program adheres to critical criteria—being aligned with ecosystem services, economically viable, socially acceptable, and readily scalable—which further supports its potential to deliver sustained productivity improvements while mitigating environmental impacts.

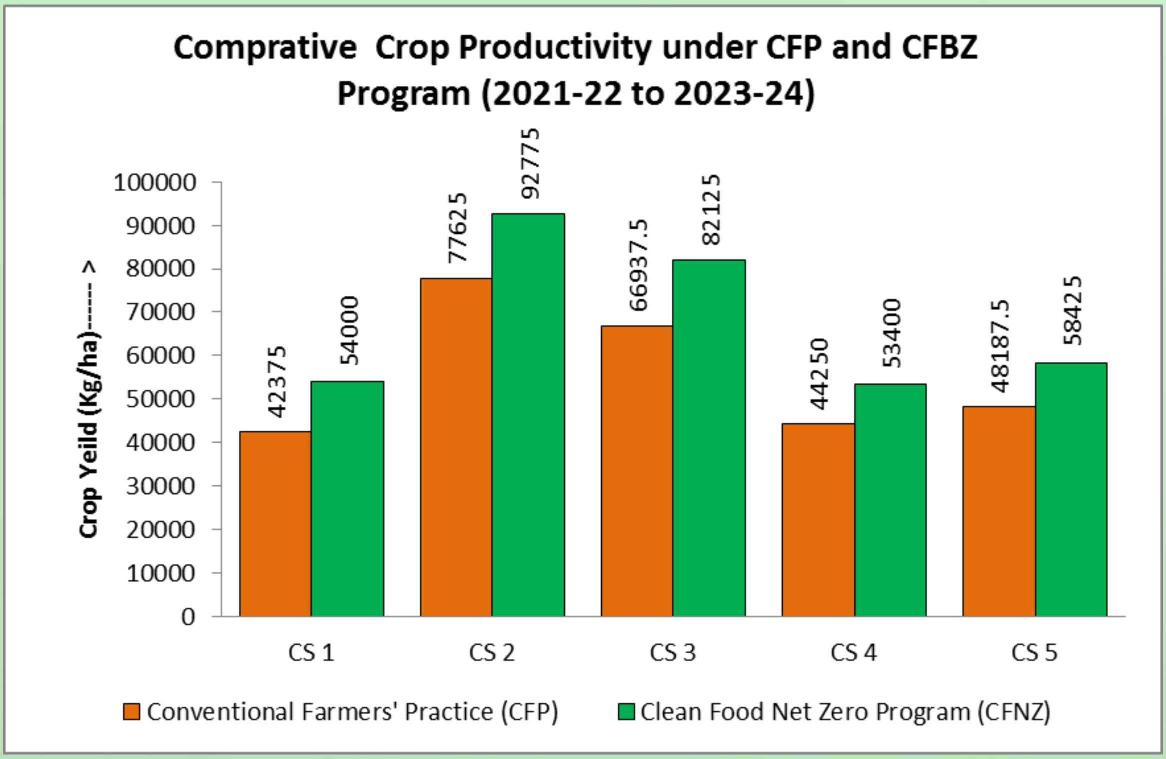


Fig 1 : Comparative evaluation of crop productivity under CFP and CFBZ program

**The Status of Food Safety in India and how 'Clean Food' Safety correlates**

In India, food safety is regulated by the Food Safety and Standards Authority of India (FSSAI) under standards aligned with the Codex Alimentarius Commission, setting a conventional maximum pesticide residue limit of 0.1 ppm in vegetables. However, for organic produce and the 'Clean Food' initiative, the limit is tightened to 0.01 ppm—not per individual pesticide, but as a cumulative ceiling irrespective of the number of pesticide groups present. From 2008 to 2018, analysis of 181,656 food samples revealed that 3,844 samples (2.1%) surpassed the prescribed limits. A focused study on 584 vegetable samples detected residues above 0.1 ppm in 83 samples (14.21%), with data showing that 34.93% of vegetables from conventional markets were contaminated, compared to only 3.85% of samples collected from the 'Clean Food' project area. Risk assessment further categorized vegetables into three groups: low/no risk (e.g., peas, cabbage, cauliflower, potato, onion, yam, spinach, and coriander with contamination in less than 20% of samples), moderate risk (e.g., French bean, cucumber, carrot, tomato, pumpkin, and ridge gourd with 20–50% contamination), and high risk (e.g., pointed gourd, brinjal, chilli, and okra with contamination in over 50% of samples). For vegetables in the high-risk category, the conventional market samples exhibited a 63.3% contamination rate, whereas those from the Clean Food project area recorded only 12.7%—an approximate 80% risk reduction. Additionally, while conventional market samples showed a single pesticide group presence in 21.6% of cases, along with 7.8% and 3.2% for two and three groups respectively, the Clean Food area reported only a 3.8% occurrence of a single pesticide group. This comprehensive data highlights that the 'Clean Food' standard stands as one of the most stringent and effective measures in minimizing pesticide exposure in India's vegetable supply.

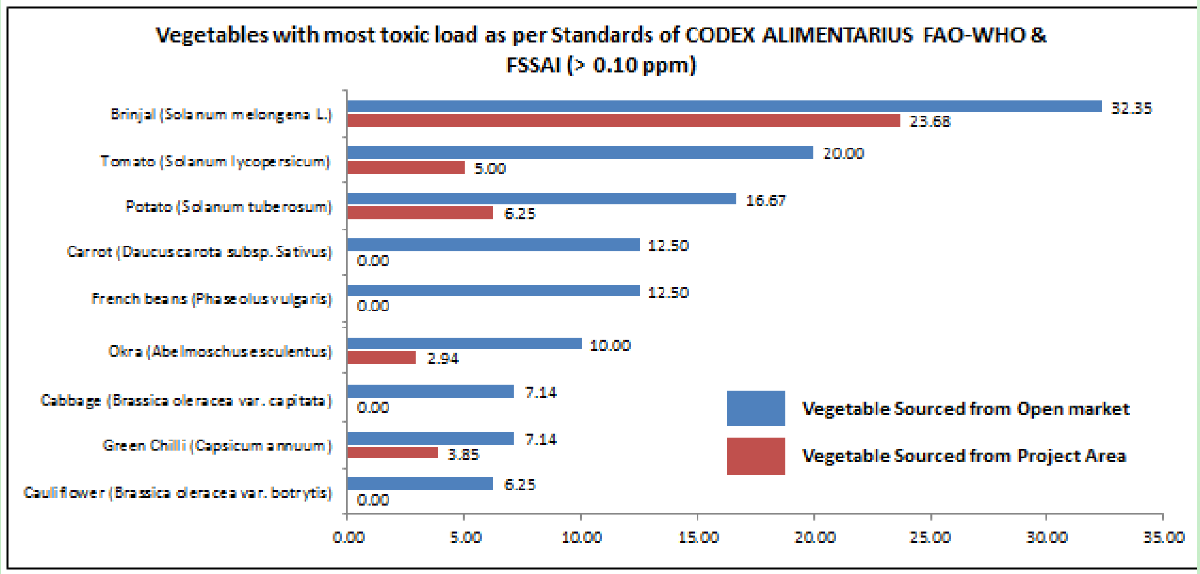

Fig 2 : Variation in percent vegetable samples having pesticide residue under conventional farmers practice and CFNZ program

**Energy transition**

Agriculture serves as both a consumer and producer of energy, providing bioenergy and food. The Green Revolution significantly increased energy use in agriculture due to the widespread adoption of chemical fertilizers, pesticides, and mechanization. Currently, the agri-food chain accounts for approximately 30% of global energy consumption, with a substantial portion occurring post-harvest and primarily derived from fossil fuels.This intensive energy use has led to environmental challenges, including soil and water pollution, and elevated $CO_2$ and $N_2O$ emissions that contribute to global warming. Therefore, enhancing energy efficiency in agriculture is vital to minimize environmental impacts, conserve natural resources, and promote sustainable agricultural practices.

Energy analysis of agricultural ecosystems provides a concrete approach to assess energy use efficiency, identify environmental issues, and evaluate the sustainability of crop production systems. In this context, an assessment was conducted on various crop sequences under the 'Clean Food Net Zero' production model, comparing scenarios with 50% and 100% reductions in chemical nitrogen use against conventional farming practices. The study focused on five major cropping sequences prevalent in the project area: Tomato-Cucumber-Coriander, Potato-Brinjal-Cauliflower, Potato-Okra-Cabbage, Brinjal-French Bean-Spinach, and Pumpkin-Okra-Cabbage.

The energy footprint plays a crucial role in agricultural sustainability, as both direct and indirect energy inputs in farming directly impact carbon emissions, resource efficiency, and environmental resilience. High energy-intensive practices contribute to greenhouse gas emissions, accelerating climate change. Notably, about 30% of the world's energy is consumed within agri-food systems, and energy use is responsible for a significant portion of greenhouse gas emissions in this sector .

The study revealed that energy use efficiency (EUE) was notably higher under the 'Clean Food' production model, especially in the Potato-Okra-Cabbage and Potato-Brinjal-Cauliflower sequences. This finding is significant, considering that energy input was also considerably higher in these two cropping sequences. An EUE greater than 2.0, along with sustained crop productivity under 'Clean Food' production, underscores the model's potential for economic sustainability and greenhouse gas mitigation within safe and sustainable agriculture.

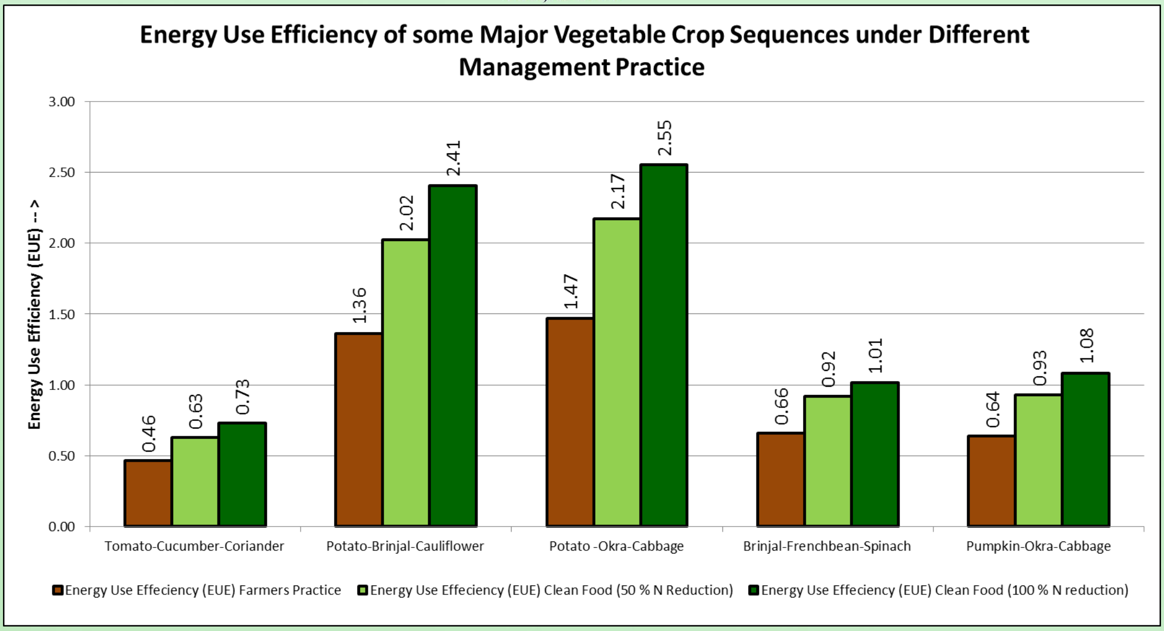


Fig 3: Comparative study of energy use efficiency under different management practice

**Comparative GHG Emission and Mitigation in Conventional and Clean Food Net Zero Crop Sequences**

A comparative analysis of different cropping sequences under varied management practices—Conventional Farmers' Practice (CFP) versus the Clean Food Net Zero (CFNZ) Program—reveals significant differences in GHG emission and mitigation potential. Using the Cool Farm Tool (Hillier, 2013), the study quantified the emissions in terms of kg $CO_2$ equivalent per hectare and per kilogram of produce. Under CFP, where chemical nitrogen fertilizers are used, the average GHG emission is positive—for instance, +0.13 kg $CO_2$-eq per kg produce—indicating net emissions. In contrast, the CFNZ approach, which incorporates either a 50% or 100% nitrogen reduction alongside the adoption of IRF Technology, achieves net mitigation, with average emissions of –0.05 and –0.23 kg $CO_2$-eq per kg produce, respectively. .

**Table 2 : Agricultural Component wise GHG (kg $CO_2$ equv./ha/year) Footprint**

| Agricultural Farm Operations (component-wise) | Chemical Crop Production Component wise | GHG (kg $CO_2$ equv./ha/year) Footprint | CFNZ under IRF Technology | GHG (kg $CO_2$ equv./ha/year) Footprint |
|---|---|---|---|---|
| Seed, Seed Treatment & Nursery Management | Chemical Seed Treatment | 8.28 | IRF Seed Treatment | 0.86 |
| | Seed Bed & Nursery | 3.08 | Seed Bed & Nursery | 1.5 |
| | Direct Seed Sowing | 12.38 | Direct Seed Sowing | 11.02 |
| Transplanting | | 6.27 | | 7.63 |
| Land Preparation | | 373.06 | | 376.11 |
| Irrigation | | 463.82 | | 488.48 |
| Weed Management | | 5.56 | | 5.72 |
| Crop Nutrient Management | Chemical Nutrient Management | 4934.97 | Nutrient Management through Novcom Compost | (-) 15269 |
| Crop Protectant | Chemical Crop Protection | 431.29 | Inhana Plant Health Mgt (IPHM) | 16.86 |
| Total GHG (kg CO2equv. /ha/year) | | (+) 6238.7 | | (-) 14330.77 |

In the detailed crop sequence analysis, sequences such as Tomato-Cucumber-Coriander, Potato-Brinjal-Cauliflower, Potato-Okra-Cabbage, Brinjal-French bean-Spinach, and Pumpkin-Okra-Cabbage showed marked shifts from positive emission values under conventional practices (ranging from 4682.9 to 8254.5 kg $CO_2$-eq/ha) to substantial negative values under CFNZ (ranging from –13085.3 to –15275.9 kg $CO_2$-eq/ha). Moreover, when only chemical pesticides were completely eliminated—as captured in the Phase-II Project—the intervention yielded an additional 18–20% reduction in GHG emissions, underscoring that nitrogen fertilizers are the predominant GHG contributors under CFP. The highest emission reduction of 7100 kg $CO_2$-eq per ha per year was observed in the Potato-Okra-Cabbage sequence, and in terms of per kilogram yield, the Tomato-Ridge Gourd-Spinach and Pointed Gourd–Cauliflower sequences emerged as the most carbon efficient (around 0.07 kg $CO_2$-eq per kg). Overall, the study demonstrates that transitioning from CFP to CFNZ—particularly with a 100% reduction in both nitrogen fertilizers and chemical pesticides—has the potential to transform agriculture from a net greenhouse gas emitter into a significant GHG sink

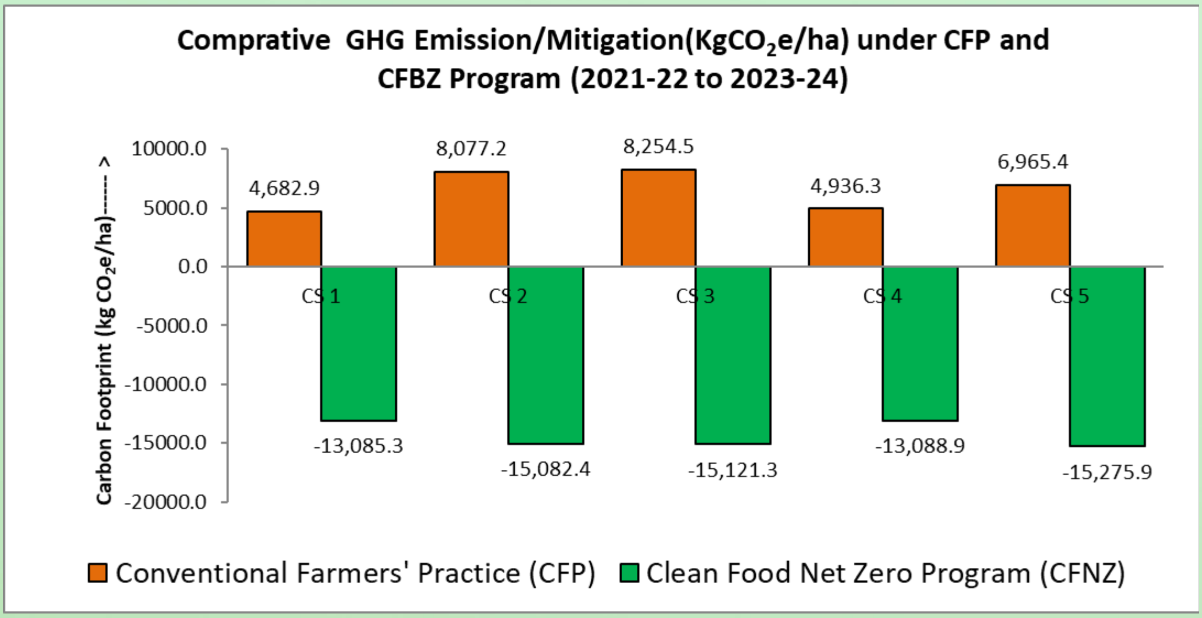

Fig 4 : Comparative assessment of Carbon footprint inder CFP and CFNZ management Program

**Economics, employment generation**

The impact of the Clean Food (CF) Model on employment generation and livelihood support is significant and multifaceted. A comparative study, as illustrated in Figures 16 and 17, indicates that adopting the CF Model can boost employment opportunities by up to 16.7 percent, demonstrating its potential to enhance local job markets and stimulate rural economies. In addition to creating more jobs, the CF Model also positively influences farmers' incomes. An analysis of gross income based on major cropping sequences—using a six-month average from December 2022 to May 2023 of farmers' procurement prices as reported by Sufal Bangla—revealed that even within conventional market frameworks, there is a potential income increase of up to 19.7 percent, even without implementing any value-added marketing strategies. This suggests that if a dedicated market chain were established for these pesticide-free, value-added products, the income potential for farmers could be amplified considerably. Such improvements not only underscore the CF Model's capacity to transform agricultural practices into more sustainable and profitable systems but also highlight its broader role in supporting rural livelihoods and contributing to overall economic development.

**Development of net zero regenerative agriculture model for livelihood sustenance and carbon mitigation**

The development of a net zero regenerative agriculture model for livelihood sustenance and carbon mitigation is a transformative approach that integrates sustainable farming practices with robust climate action measures. By merging strategies such as the Clean Food Net Zero (CFNZ) Program and Inhana Rational Farming (IRF) Technology, this model focuses on reducing reliance on chemical nitrogen fertilizers and pesticides, thereby lowering greenhouse gas emissions while enhancing soil health and crop productivity. Regenerative practices—bolstered by advanced technologies like Novcom composting—accelerate organic matter recycling, improve nutrient cycling, and promote microbial biodiversity, which in turn increases carbon sequestration and creates a net carbon sink. This holistic model not only improves yields by up to 22% and raises income potential by nearly 20% compared to conventional practices but also fortifies the socio-economic conditions of resource-poor, small, and marginal farmers. Ultimately, by aligning agricultural productivity with environmental resilience, the net zero regenerative agriculture model offers a sustainable pathway to secure both the livelihoods of farming communities and the long-term stability of the climate.

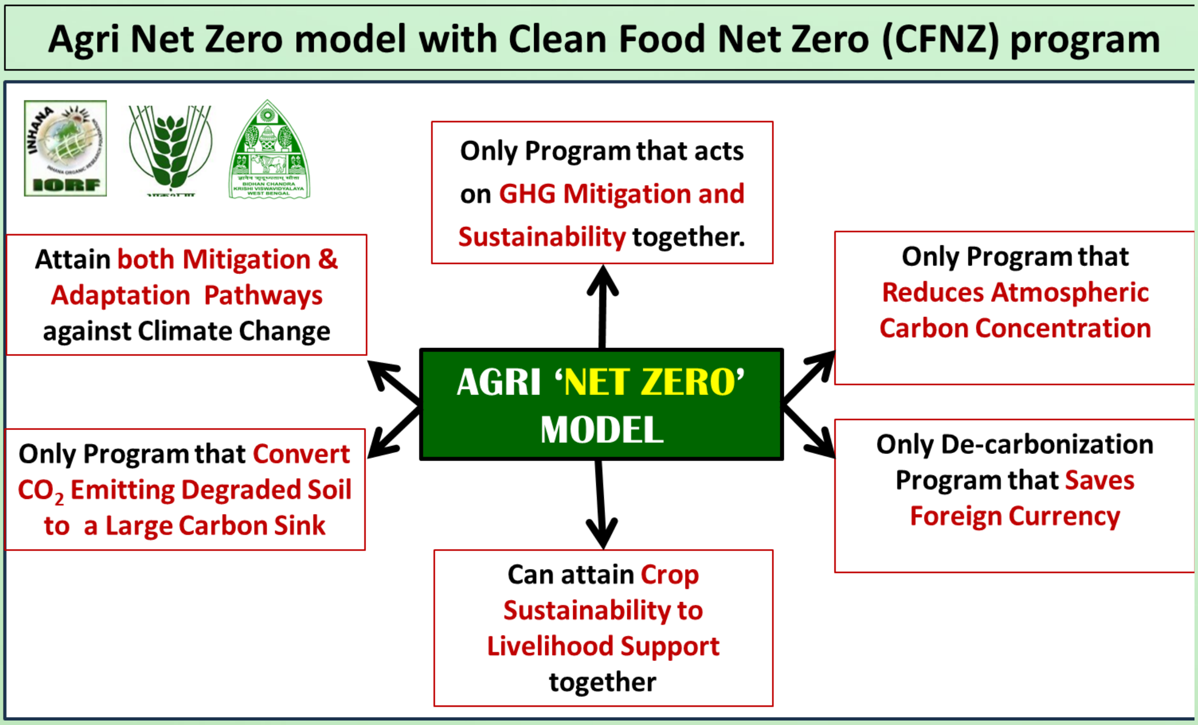


Fig 5 : Development of Agri-Net Zero model with adoption of CFNZ program

**Conclusion**

The comprehensive studies and analyses presented affirm that integrating a net zero regenerative agriculture model can substantially transform conventional farming practices into sustainable, climate-resilient systems. By adopting innovative practices such as the Clean Food Net Zero (CFNZ) program and Inhana Rational Farming (IRF) Technology, agriculture can transition from being a major greenhouse gas emitter to acting as a robust carbon sink. This transformation is supported by enhanced soil and plant health, exemplified by improved crop yields, nutrient cycling, and effective microbial activity as observed in advanced composting technologies like Novcom Composting. Furthermore, the integrated model not only mitigates environmental impacts—achieving marked reductions in greenhouse gas emissions—but also bolsters rural livelihoods by increasing employment opportunities and farmers' income. Ultimately, these findings underscore the viability of a regenerative agricultural framework that aligns economic sustainability with environmental stewardship, offering a replicable blueprint for addressing the twin challenges of climate change and food security on a global scale.

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