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Diminishing Water-Energy-Food Nexus Approach and Sustainability in Agricultural Practices: A Study in Saharanpur District, Uttar Pradesh, India

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ABSTRACT

Background: Western Uttar Pradesh in India is facing escalating extraction of groundwater through privately owned tube wells for irrigation which raises concern for environment and sustainability. The major reasons for increasing groundwater exploitation are inefficient water supply through Government superficial canal water, changing cropping pattern towards cash crops and subsidized power utility used in groundwater pumping. It has resulted in diminishing water-energy-food (WEF) nexus approach and sustainability in agriculture practices in the region.

Methods: Data were collected through semi-structured in-depth interview technique from 100 farmers of two villages of Saharanpur district in western Uttar Pradesh in India. Date were also collected from 11 other stakeholders who are associated with agriculture sectors. Participatory rural appraisal (PRA), focus group discussion (FGD) and case study techniques were also used for strengthening the quality of data.

Result: The cultivation practices in Saharanpur district have completely transformed. It has changed from subsistence agriculture, involving diverse crops, animal husbandry and horticulture to primarily sugarcane, wheat and rice crops. The average percentage of the use of groundwater is 83% and the superficial canal water is 17%. Out of total 100 sample size of farmers in Jakhwala and Rankhandi villages of Saharanpur district, only one farmer was using innovative methods of irrigation. Only two farmers tried to economise water usage by efficient surface irrigation. Similar are the other findings. The study suggests that farmers should be trained to improve the situation of agriculture cropping pattern by encouraging crop diversification and promote the use of drip and sprinkler methods of irrigation.

Key words: Agricultural practices, Groundwater exploitation, Sustainability, Sustainable development goals, Water-energy-food-nexus.

INTRODUCTION

WEF nexus approach and sustainability in agricultural practices are two important aspects for the growth of agriculture sector and improving farmers' income in the long run. Groundwater utilization has become vital in the agriculture sector in India. According to a Report of the year 2020 (Central Ground Water Board, 2020), India's total annual groundwater extraction was anticipated 244.92 billion m^3, with approximately 89% of it was utilized for irrigation in agriculture. Uttar Pradesh is one of the most productive States in India with respect to agriculture due to the presence of largest groundwater reservoir beneath the Gangetic Alluvial Plain (Sinha *et al.*, 2016). However, due to unregulated extraction and over utilization of groundwater, the decreasing water levels are significantly affecting even the water-abundant alluvial region of the State.

Looking with the lens of WEF nexus approach and sustainability in agricultural practices, it is noticed that there is a direct relationship of increase in groundwater exploitation with production of cash crops such as sugarcane, wheat and rice in western Uttar Pradesh. The advancement of groundwater pumping technology has resulted into the growth of agricultural production thereby benefiting the farmers (Smilovic *et al.,* 2015). But the nature of these benefits to the farmers are immediate, temporary, costly and at the cost of environmental degradation. It is resulting in diminishing WEF nexus approach and sustainability in agriculture practices. Furthermore, irrigation by tube wells is more convenient to the farmers due to the proximity of pumping stations to the point of water utilization and at affordable cost (Zhu *et al.,* 2007). But over extraction of groundwater for irrigation has raised serious concern for environment and sustainability.

Most of the studies interpret groundwater management and irrigation governance as separate problems rather than interconnected. This can be seen in the research study

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of National Aquifer Mapping Programme in which hydro-geological data including assessment of Saharanpur district in western Uttar Pradesh has been developed (Central Ground Water Board, 2020). A study analyses the importance of groundwater governance supported by both scientific mapping and community participation (Kulkarni *et al*., 2015). Only a few studies emphasize on adoption of WEF nexus approach and sustainability in agricultural practices for effective management of groundwater, electricity and food security (Mukherji, 2020). Hence the present study is highly relevant.

The WEF nexus approach focuses on the interconnected relationships among water, energy and food systems through the lens of sustainability. This conceptual approach emerged during the late 20th century and gained significant recognition in the early 2000s (Leck *et al.,* 2015). The Bonn 2011 Nexus Conference, held in Germany, served as an essential platform for promoting the WEF nexus strategy (Hoff, 2011). The significance of the WEF nexus was further reinforced at the United Nations Conference on Sustainable Development (Rio+20) in 2012 (Leck *et al.,* 2015). This approach prioritizes resource security through cross-sectoral integration, demonstrating how resource usage and availability are interconnected (Biggs *et al.,* 2015). The framework additionally highlights the critical role of socio-economic factors in resource governance, particularly through considerations of accessibility, equity and cost-effectiveness (Mabhaudhi *et al.,* 2021).

Multiple studies indicate that sustainable development goals (SDGs) cannot be achieved by treating water, energy and food sectors in isolation. One of the study is by where usage of integrated nexus approach is emphasised for achieving SDGs in South Asia (Mitra *et al*., 2020). Unsustainable agricultural practices, flat-rate or free electricity for irrigation and poor water management of superficial canal water by State have collectively led to groundwater exploitation and energy inefficiency (Mukherji, 2020). There are strong interconnections and interde-pendency among the three sectors, but lacks coordination for sustainable development (Mondal *et al.,* 2023). WEF nexus approach and sustainability in agricultural practices require cross-sectoral governance, inclusive stakeholder engagement and the integration of ecosystem services into policy frameworks (Bhaduri *et al*., 2015). A review on sustainability in different sectors including agriculture emphasizes that inefficiencies and mismanagement in one area can trigger negative feedbacks and resource scarcities in others (Zarei *et al*., 2021). A study conducted in Saharanpur district examined the economic and environmental benefits of agroforestry systems demonstrating that tree-crop integration improves soil health, biodiversity, farm productivity, income diversification and carbon sequestration (Katariya *et al*., 2025).

The WEF nexus approach has gained significant momentum as an emerging research priority since the establishment of the Sustainable Development Goals in 2015 (Mabhaudhi *et al*., 2021). The 17 SDGs, adopted by the United Nations, were designed to tackle global challenges by 2030 through an integrated approach that addresses economic, social and environmental dimensions simultaneously (United Nations, 2017). Within this framework of 17 SDGs, some goals hold particular significance for addressing the problem of diminishing WEF nexus approach and sustainability in agriculture practices. Goal 2 focuses on eliminating hunger, achieving food security, improving nutrition standards and advancing sustainable agricultural practices. Goal 7 emphasizes ensuring universal access to affordable, reliable, sustainable and modern energy services. Goal 12 centres on establishing sustainable consumption and production patterns across all sectors. There is a need to focus on the importance of WEF nexus approach and sustainability in agricultural practices through integrated management, improved efficiency and policy alignment to protect ecosystems. Keeping this perspective in view, research framework of WEF nexus approach and sustainability in agricultural practices have been elaborated in the present study.

MATERIALS AND METHODS

This study was conducted by the authors affiliated to Indian Institute of Jodhpur, India during 2023-2024 in Uttar Pradesh, India which is the most populus State and ranks fourth in terms of area in India. It is situated in the fertile plain of the Indo-Gangetic region (Singh, 2020). Agriculture serves as the primary economic foundation of the State and heavily depends on groundwater. The State is divided into four geographical regions; Bundelkhand, Central, Eastern and Western. In western region of Uttar Pradesh, sugarcane crop is predominantly cultivated followed by wheat and rice. The State undergoes low level of rainfall compared to the national average and western Uttar Pradesh witnessed a more significant decline in rainfall compared to the other regions of the State (Deo *et al*., 2024). The high agricultural intensity in western Uttar Pradesh caused by the excess utilization of groundwater is leading to a rapid depletion of groundwater level. Hence, diminishing the WEF nexus approach and sustainability in agricultural practices.

The rationale for selecting Saharanpur district in western Uttar Pradesh as a research site is the significant prevalence of privately owned tube wells which are used for groundwater exploitation and the notable rise in cash cropping intensity of sugarcane, wheat and rice in the region. The district encompasses a total irrigated area of 375,604 acres, with groundwater sources providing irrigation for approximately 84% of this area (Central Ground Water Board, 2020). Overall, the district has significant groundwater depletion. This is evident from the classification of its 11 blocks, with five blocks categorized as over-exploited, four as critical, one as semi-critical and only one as safe.

Two villages namely, Rankhandi (larger) and Jakhwala (smaller) were selected from the Deoband sub-district of

Saharanpur district for this study. These villages were selected as they differ in size and population, offering two distinct demographic patterns. Both the villages also have access to a variety of irrigation facilities, making them suitable for studying WEF nexus approach and sustainability in agricultural practices. Larger village had 9724 registered voters in 2021. The village covers about 8600 acres of agricultural land. The smaller village had about 2430 voters in 2021. It covers about 1150 acres of agricultural land. The main crops in both the villages are sugarcane, wheat and rice. A third village, Nandi Firozpur, located in the Baliakheri sub-district of Saharanpur district was also selected for a case study highlighting sustainable agricultural practices.

The main objective of the study was to understand the WEF nexus approach and sustainability in agricultural practices. The study's primary data collection strategy centred on conducting detailed semi-structured in-depth interviews with farmers. The sampling strategy involved selecting approximately 5% of tube well owners as the study sample, comprising 80 farmers from the larger village (Rankhandi) and 20 farmers from the smaller village (Jakhwala) from Deoband sub-district of Saharanpur district in western Uttar Pradesh. A case study was also conducted in Nandi Firozpur village located in the Baliakheri sub-district of Saharanpur district. 11 other stakeholders from the Saharanpur district were also interviewed who were involved directly or indirectly in agriculture system representing Government Officials, Irrigation Department Officials and Agriculture Department Officials.

PRA, FGD and case study techniques were also used for data collection. Total 3 PRAs were conducted with the group of farmers to prepare socio-economic and demographic profile of the villages. Two PRAs were conducted in the larger village and one in smaller village. To strengthen the quality of data, FGDs were conducted with the farmers in both the villages. Two FGDs in larger village and one in smaller village were conducted. Case studies were conducted to document the sustainable agricultural practices and explore the alternative models or solutions that could be applied in the region for strengthening WEF nexus approach and sustainability in agricultural practices. Two case studies were conducted in each of the villages; larger and smaller and one case study in third village. PRA technique was used for developing the socio-economic profile of villages and obtaining numerous facts and figures regarding the community's infrastructure, agricultural cropping pattern, irrigation systems, economy, other income generating activities, population, education and other factors. FGDs were conducted to cover the issues related to WEF nexus approach, climate change resilience, market linkages of agricultural produces and benefits of different schemes being implemented for the welfare of farmers. The research design is given in Fig 1.

RESULTS AND DISCUSSION

Historical progression of agriculture sector in western Uttar Pradesh

The rise in population increased the pressure on water supplies in Indian agriculture during the 20th century. Increasing agricultural intensity with continuous irrigation throughout the year emerged as the sole method to enhance the agriculture productivity. The tube well technology was pioneered by the British engineers in the Indo-Gangetic basin. The United Provinces (now Uttar Pradesh) made extensive efforts to encourage groundwater irrigation in the 1930s (Kahnert and Levine, 1993). Newly developed tube well technology was vigorously promoted by the administration of United Provinces (Shah *et al*., 2012). Government also implemented public tube well infrastructure and provided small farmers with subsidized

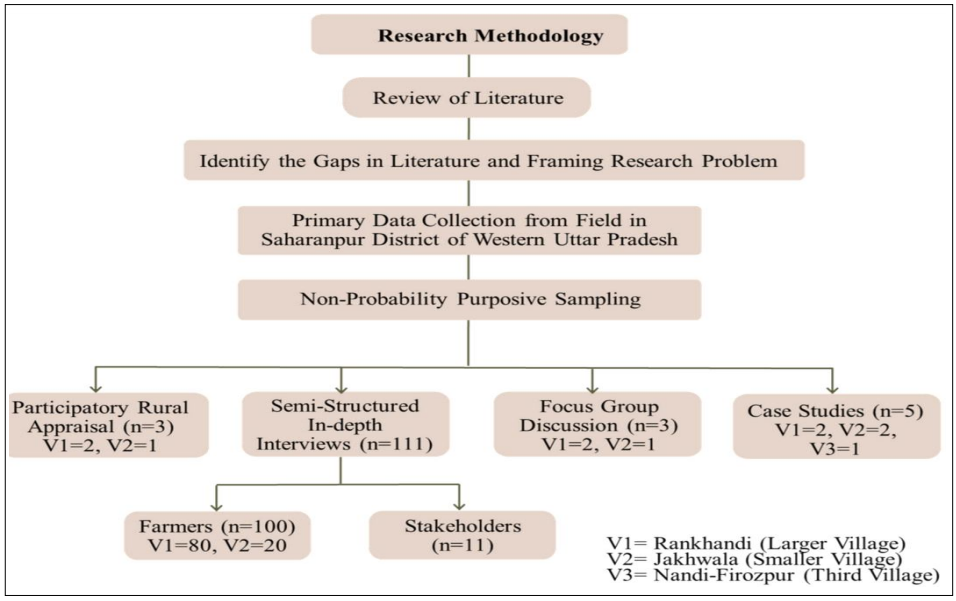

Fig 1: Research design.

irrigation (Shankar, 1992). Green Revolution placed significant emphasis on irrigation as a critical input for augmenting agricultural output. From 1964 to 1966, India experienced three consecutive droughts, leading to its reliance on food assistance from the United States (Shah *et al.,* 2012). During this period and onward, Government vigorously supported the promotion of tube well irrigation in the Indo-Gangetic plains (Shah *et al*., 2012). Furthermore, surface irrigation through canal failed to adequately accommodate the growing water demands of water-intensive crops such as sugarcane, wheat and rice in western Uttar Pradesh (Mukherji, 2020).

There was shift from mixed and diversified farming system to cash cropping system with the advent of Green Revolution. For better production in cash crops, farmers started using high yielding variety (HYV) seeds, fertilizers, chemicals and pesticides and replaced own saved local seeds and organic / compost manure. The newly adopted farming system required more water for irrigation. The post Green Revolution era saw a rapid surge in tube well installation across Uttar Pradesh. Shift from canals to tube wells can be seen in the Fig 2 by noticing the huge gap between the net area irrigated by the two sources (canal and tube well) in Saharanpur district.

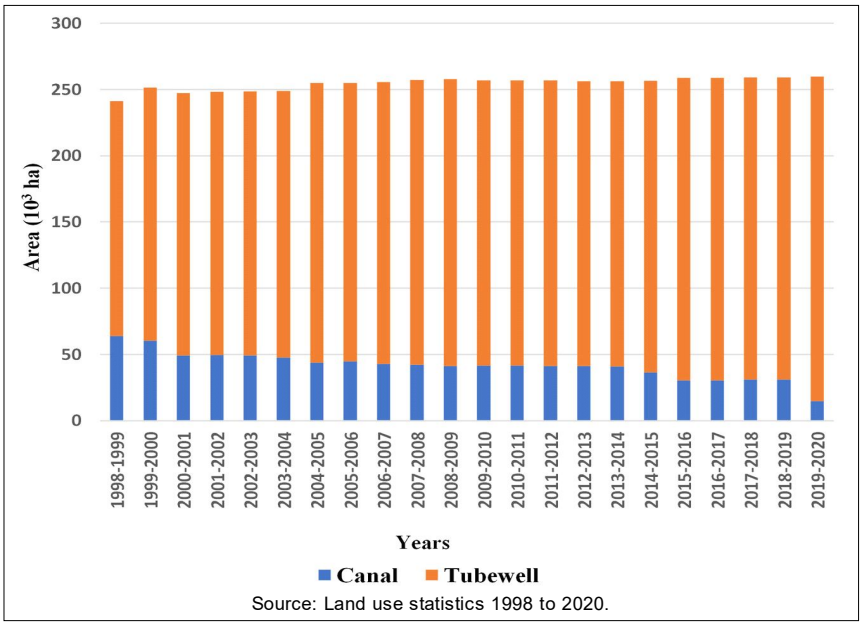

Fig 2: Area irrigated (source wise) in Saharanpur district for the year 1998-2020.

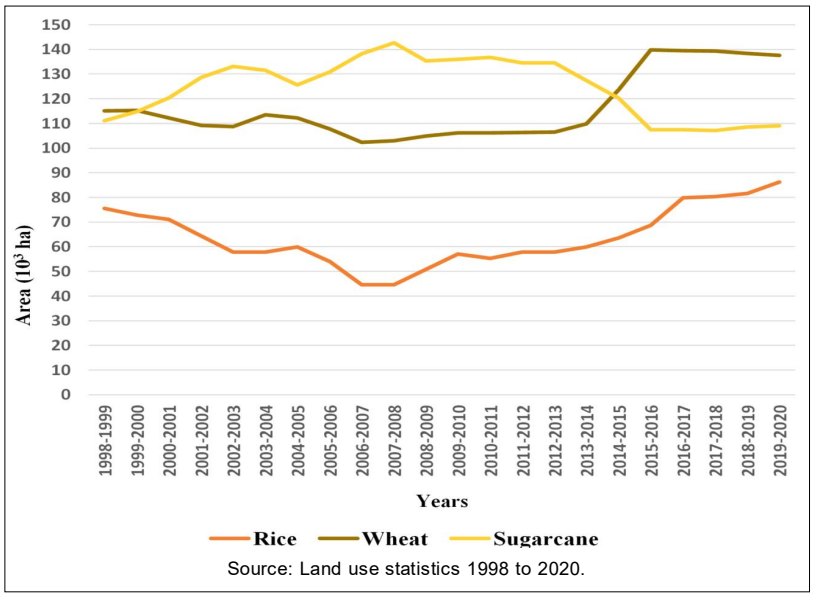

Fig 3: Area irrigated (crop wise) in Saharanpur district for the year 1998-2020.

In the last four decades, there has been a complete transformation in cultivation practices in Saharanpur district. Previously, subsistence agriculture was practiced, which involved a mixture of diverse crops, as well as animal husbandry and horticulture. The irrigation relied mostly on rainwater and up to some extent on canal water in the command area. The use of HYV seeds, fertilizers, chemicals and pesticides was minimal. Over time, the variety of crops has decreased to sugarcane, wheat and rice. The local farmers rely heavily on cash crops, particularly sugarcane, due to the presence of sugar mill factories in the district. Additionally, the method of deep irrigation by tube wells was followed by farmers instead of using surface level irrigation. This significantly impacted the level of groundwater. Fig 3 shows very large area irrigated by these crops in Saharanpur district from 1998 to 2020.

Government policies concerning irrigation governance

The Government policies and initiatives played significant role in shaping groundwater utilization and lacked effectiveness for long-term resource conservation in the region. In India, groundwater rights are governed by the common law of land ownership (Verma and Dimri, 2020). Hence, the landowners possessed the rights to groundwater and extract the groundwater without any regulation. The State oversees management of the water. The Government policies and schemes of subsidies on electricity for tube wells, fertilizers, cultivation of cash crops such as sugarcane, wheat and rice are contributing in groundwater exploitation (Sahu and Pradhan, 2024).

The primary objectives of the power subsidies were to enhance agricultural productivity, alleviate poverty and mitigate the risk of famine. The subsidies and groundwater utilization have been credited as the key factors that have laid a solid groundwork for the Green Revolution in India (Gandhi and Bhamoriya, 2011). However, even after evolving economy, the subsidies have remained unchanged, leading to excessive exploitation of groundwater and placing a financial strain on the Government. Agriculture in Uttar Pradesh now receives power at a flat rate under Uttar Pradesh Power Corporation Limited (UPPCL) after a revision in September 2019 (Kishore *et al*., 2021). The agricultural activities in Saharanpur district are causing environmental stress due to the gradual decline in canal water supply and groundwater levels. During 2009-2018, pre-monsoon water levels declined in most wells, with 39 wells showing decline rates of 1-81 cm/year and rose in only 5 wells with rates of 0.64-35.16 cm/year (Central Ground Water Board, n.d.). As acquired insights from the fieldwork, presently it is necessary to excavate the wells to a depth of 200 to 250 feet to access groundwater which was around 100 to150 feet or less around 2000. The modern resource-conserving technologies such as micro-irrigation, drip irrigation and sprinkler irrigation cannot be easily used in these water-intensive crops.

Main findings of the field data analysis

Qualitative and quantitative primary data have been collected from the field from farmers and other stakeholders. Main findings of the field data analysis are given in Table 1.

Table 1: Main findings of the field data analysis.

Parameters	Summary of main findings
Farmers owning tube well	i) These farmers ranged in the categories of small, medium and large farmers in terms in land holding. The average size of land holding was 10.025 acres per family. ii) 68% of the farmers were also using canal water in addition to their own tube wells. iii) On average, groundwater accounted for 83% of irrigation sources, while canal water contributed 17%. iv) The average cost of the electricity use was Rupees 15,343.75 per tube well connection per annum. v) 11% of the famers settled their electricity bills monthly, 12% paid quarterly, 40% made annual payments and 37% were defaulters awaiting Government declaration of the electricity bill waive off. vi) Out of total 100 sample size, only one farmer was using innovative methods of irrigation such as drip irrigation / sprinkler irrigation. This reflected that farmers were not adopting innovative methods of irrigation. vii) Out of total 100 sample size, only two farmers tried to economise water usage in irrigation by efficient surface irrigation as compared to deep irrigation. viii) Sugarcane, wheat and rice were the major crops grown by the farmers.ix) Only 21% of the farmers practised mixed and diversified cropping pattern in their agricultural fields. x) 60% of farmers received agricultural guidance through information and support related to agricultural matters like; soil testing and use of seeds, fertilizers and pesticides etc. from Government Agriculture Department. xi) 84% of the farmers have taken loan under Kisan (Farmer) Credit Card Scheme. xii) 21% of farmers benefited from the Government loan waiver scheme. xiii) 90% of farmers recognized climate change's impact on agriculture but lacked knowledge about the climate change resilient farming practices. They were reluctant to adopt innovations, remaining reliant on cash crops like sugarcane, wheat and rice.

Table 1: Continue....

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Other stakeholders	i) Irrigation from the government's command area and canal slots is inefficient especially in summer, forcing the farmers to rely on private tube wells. ii) Agricultural policies addressing the WEF nexus are developed and enforced by separate departments, leading to fragmented approaches that undermine policy effectiveness. iii) Farmers benefitted from heavily subsidized electricity rates, yet frequent delays or non-payment which are driven by expectations of political waivers, place financial strain on power utility companies. iv) Despite government incentives for water-saving irrigation techniques like drip and sprinkler systems, uptake remains low due to the prevalence of water-intensive crops in the area.
FGDs with all types of farmer groups (tube well owners as well as non-owners with all socio-economic categories.	i) Farmers in both the villages were heavily depended on private tube wells; mostly benefiting wealthier landlords. This reinforces socio-economic disparities and increase in informal water markets. ii) Instead of making monthly payments that qualified for subsidy benefits, most farmers opted for annual bill settlements. This backfired when waivers were not granted or delayed, forcing farmers to accumulate interest charges on their outstanding bills, negating the benefits of the subsidy scheme. iii) Dissatisfied with their circumstances, farmers suggested loan waivers, access to low-interest credit, effective implementation of minimum support prices (MSP), enhanced subsidies and stronger promotion of farmer producer organizations (FPO), all of which were deficient in the area.
Case studies on sustainable agricultural practices	i) In the larger village, two brothers continued their father's horticultural legacy, which started in the 1970s when their father planted mango orchards on his 18-acre plot despite of opposition from the locals. They currently manage 12 acres of fruit crops, such as pomegranates, guavas and mangos, using sustainable practices including integrated pest management and crop rotation. ii) In the larger village, a pond with Sarovar ID 34439 and capacity of at least 1 acre at the northern entrance of the village near Kaleshwar Mahadev Temple was created under the Amrit Sarovar Yojana to boost the water table and support biodiversity. iii) In the smaller village, two enterprising brothers expanded their father's legacy by combining horticulture with conventional farming on their 30-acre holding. They made investments in contemporary techniques, such as sprinkler irrigation and underground piping, after their father first turned to horticulture as a way to safeguard land under the Land Ceiling Act. Land Ceiling Act was implemented to restrict the maximum agricultural landholding to encourage equitable distribution. By shifting to horticulture, the father could save and justify retaining the family's 30-acre holding. This endeavour has since developed into a passion backed by modern methods. iv) In the smaller village, a pond reputed to date back to the Mahabharata era was restored through the Amrit Sarovar Yojana with Sarovar ID 34437 and capacity of more than 1 acre. v) A farmer from Nandi-Firozpur village who received the Padma Shri developed an innovative mixed farming method that included growing sugarcane, water chestnuts, fruits, vegetables and flowers. In addition to improving soil health and lowering dependency on postponed sugarcane payments, his well-planned crop rotations produce year-round revenue.

Suggested recommendation to strengthen WEF nexus approach and sustainability

Some recommendations are suggested here to strengthen WEF nexus approach and sustainability in agricultural practices.

1. Farmers should be trained and motivated to take grassroots action to improve the situation of agriculture cropping pattern in the region to encourage crop diversification. According to a study conducted in Kerala, black gram alongside maize or finger millet in coconut gardens significantly boosts productivity and improves soil nutrient balance, which in turn increases resource use efficiency and sustainability in agricultural practices (Pillai and Radhakrishnan, 2024).
2. Government should boost the market for agriculture commodities by providing reasonable MSP for different commodities so that they can adopt multiple cropping pattern in place of cash cropping and get the best price for their produces.
3. Government should also promote FPOs and build their capacity so that farmers collectively can face the onslaughts of production process and markets. They can minimise their production expenses and increase their income. According to a study conducted in Maharashtra, the main challenges for farmers participation in FPOs are insufficient financial support for FPO operations, inadequate infrastructure and capacity building, limited government support, poor market information access and farmers' lack of awareness about the FPO concept (Salokhe, 2025).
4. Drip and sprinkler methods of irrigation should be promoted and their implementation must be monitored continuously.

5. Government can charge fair price from farmers without providing subsidy for usage of electricity (Mukherji, 2020). Over usage of water and electricity may be decreased by implementing a smart tariff and appropriate power supply rationing for the agricultural sector.
6. The scheme of Amrit Sarovar Yojana which was started by the Union Government, aims to revitalize and develop water bodies in every Indian district, supply water to the surrounding communities and lessen groundwater exploitation. Participation of community people should be encouraged by the Government in such schemes.
7. The conflicting WEF scenario requires logical management of groundwater, power utility and cropping pattern in a comprehensive and integrated way with its connection to the environment. Thus, Agriculture policy should be framed keeping in view WEF Nexus approach and sustainability in agricultural practices.

CONCLUSION

In this research, the WEF nexus framework and agricultural sustainability principles serve as analytical tools to examine interconnected challenges including water scarcity, adequate energy infrastructure requirements and long-term food security assurance. Furthermore, SDGs cannot be achieved by treating water, energy and food sectors in isolation. Findings reveal that intensive cultivation of cash crops particularly sugarcane, wheat and rice has driven a disproportionate rise in groundwater extraction, undermining the integrated resource management envisioned by the WEF nexus. It has resulted in diminishing WEF nexus approach and sustainability in agricultural practices in the region. Agricultural practices in western Uttar Pradesh underwent major transformations because of Green Revolution initiatives. It shifted farming from diversified systems toward water-intensive monocultures. There is a need to transfer policy support from cash crops to mixed and diversified crops. The present study will be highly relevant for future research in agriculture sector on WEF nexus approach and sustainability in agricultural practices with various perspectives such impact of mixed and diversified farming system, climate change resilience, use of information communication technology, reducing input cost and increasing output and increasing the famers' income and many more.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institution. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct and indirect losses resulting from the use of this content.

Conflict of interest

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