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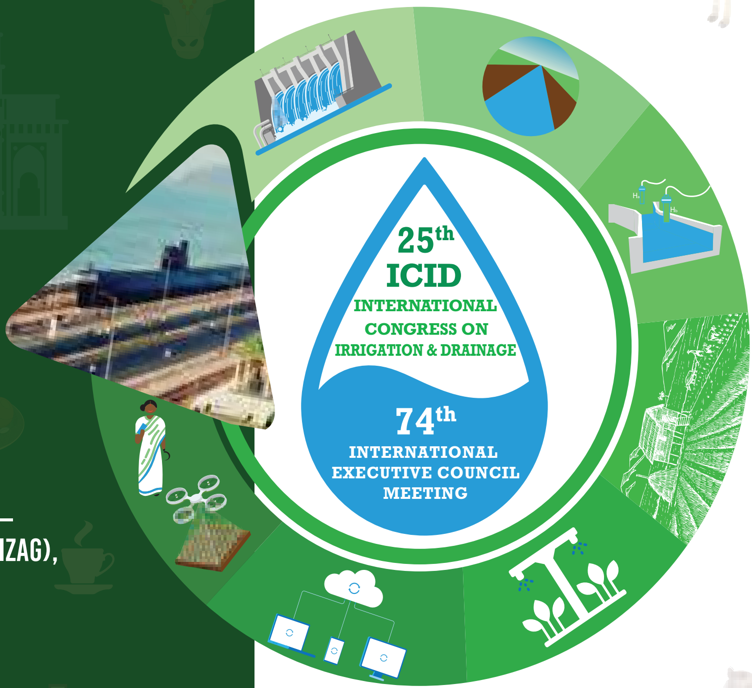

PROCEEDINGS

INTERNATIONAL WORKSHOP ON THE WATER-ENERGY-FOOD-NEXUS: IMPLEMENTATION AND EXAMPLES OF APPLICATION

TACKLING WATER SCARCITY IN AGRICULTURE

LUTTER CONTRE LA PENURIE D'EAU DANS L'AGRICULTURE

INTERNATIONAL COMMISSION ON IRRIGATION AND DRAINAGE

COMMISSION INTERNATIONALE DES IRRIGATIONS ET DU DRAINAGE

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The International Commission on Irrigation and Drainage (ICID), established in 1950 is the leading scientific, technical and not-for-profit Non-Governmental Organization (NGO). The Commission through its network of professionals spread across more than a hundred countries, has facilitated sharing of experiences and transfer of water management technology for over six decades. ICID supports capacity development, stimulates research and innovation and strives to promote policies and programs to enhance sustainable development of irrigated agriculture through a comprehensive water management framework.

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- **F** Facilitate Capacity Development

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Proceedings

International Workshop on
The Water-Energy-Food-Nexus: Implementation and Examples of Application

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September 4, 2023

Working Group on Water Food Energy Nexus (WG-WFE-N)

Prof. Dr Ragab Ragab
Chairman and President, ICID
Wallingford, UK

Presented at:

25th ICID Congress and 74th IEC Meeting,
1-8 November 2023
Visakhapatnam (Vizag), Andhra Pradesh State, India

International Workshop on

The Water-Energy-Food-Nexus: Implementation and Examples of Application

This Workshop is being organised under the auspices of the International Commission on Irrigation and Drainage (ICID) Working Group on **"Water-Energy-Food Nexus."** It is held in conjunction with ICID's 25th ICID International Congress and the 74th International Executive Council Meeting (IEC). This Workshop is a third in a series of Nexus Workshops. started in Bali, 2019 then 2022 in Adelaide in 2022 and this year in Visakhapatnam (Vizag), Andhra Pradesh State, India, 2023.

ISBN: 978-81-89610-36-4

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Preface

The Water-Energy-Food Nexus approach is a holistic vision of sustainability that recognises and tries to strike balance between the different goals, interests and needs of people and the environment. The challenges ahead are, increase global energy demand by 30-40%, global food demand by 70-100% and water use by 50% by 2050. Irrigation globally consumes around 70% of freshwater resources. This water is becoming increasingly scarce. Irrigation requires energy. Therefore, improving water and energy use efficiency and productivity in agriculture practices will be valuable. The old concept: Crops: “more crop per drop” has now changed to a new concept based on the Water Food Energy Nexus: “more crop per drop per kilowatt “.

The nexus can stimulate innovation and use of new technologies for example if increasing irrigated land is limited by the available traditional energy sources, the authorities might adopt non-conventional innovative energy sources (hydropower, wind power, solar energy, etc.). In addition, the nexus could also lead to a better governance arrangement via cross-sectoral water-food-energy frameworks and polices. It could also lead to developing integrated management models accounting for WFE and impact of climate and population changes

Benefits of WEF Nexus implementation at field level include, improvements in water productivity, better agronomic and engineering management, improved energy use efficiency, improved agriculture water management, e.g. rain water harvesting and soil water conservation technologies, improved crop varieties with high water use efficiency and improved agronomic practices, e.g. intercropping, micro-irrigation systems (drip and sub-surface irrigation) in place of macro-irrigation systems (overhead and sprinkler type irrigation) and practicing deficit irrigation to increase water productivity. These are important in achieving SDGs 2, 6, 12, 13 and 15.

At national level, the benefits of the nexus implementation include adopting more holistic approach in planning: e.g. if the national targets is to increase area under irrigation, then the plan should ensure matching available water and energy resources. In addition, the integrating plan will require investments in efficient irrigation schemes for enhanced economic development, resilient food systems and strengthening farmers’ capability to adapt to climate variability and change, and promote the cultivation of less water consuming crops suitable to local environments.

The objective of the workshop is to bring together experts from all over the world to share information, experience, and views on how to implement the water-energy food nexus in agriculture. The papers of the proceedings will show examples of application and address the three elements of the Nexus: Water, Food and Energy. The Workshop papers covered:

1. Water-Energy-Food–nexus at field, regional and country scales.
2. Quantification of the Water security Index, Energy Security Index, Food security Index and the overall WEF Index.
3. The trade-offs between the WEF nexus elements
4. The spatial distribution of WEF Index across the scales (local, region, state, and country)
5. Socio-Economic analysis of the nexus application.

6. Management practices that promote the Nexus.
7. Institutional and Governance issues in implementing the Nexus.

Finally, I would like to acknowledge the help of Dr. Nadine Depre (my wife) in reviewing, revising, and editing the different papers submitted to this workshop. In addition, I would like to express my sincere appreciation and gratitude to the ICID Central Office for their efforts and cooperation during the course of the preparation of this Proceedings and for setting up the necessary arrangements and the program of speakers for the workshop.

Prof. Dr Ragab Ragab
Chairman WG-WFE-N, and
President, ICID, Wallingford, UK

NAVIGATING THE WATER-AGRICULTURE-ENERGY NEXUS FOR SUSTAINABLE DEVELOPMENT: LESSONS FROM MOROCCO

Domitille Vallee, Lahcen Kenny, IAV Hassan II,
Anais Rondier, and Dubravka Bojic[1]

ABSTRACT

The 2030 Agenda and the Sustainable Development Goals have given a strong impetus to the debate on the nexus between several sectors and have highlighted the practical need for increased coordination, cooperation and cross-sectoral policy coherence to achieve sustainable development. These processes provide a unique opportunity to advance policy coherence between water, agriculture, energy, and ecosystems- towards the three critical sectors to poverty reduction and sustainable development. The Nexus approach has been used in a variety of contexts as a valuable framework to exchange information, better understanding and framing the links between relevant sectors with the ambition to align policies for sustainable development. While the nexus debate has been useful in drawing attention to sustainability challenges and the complex interdependencies between sectors, addressing the governance of the nexus has proven difficult. This paper will address the issue of using the Nexus approach to identify and describe the complex water-agriculture-energy-ecosystems interconnections and discuss current and innovative institutional and governance mechanisms that can help reconcile the competing water needs of different economic activities, in particular agriculture and energy, and different interests and perspectives of relevant stakeholders, while preserving the sustainability of water resources in the current context of water scarcity and climate change in the NENA region.

Global projections indicate that the demand for fresh water, energy and food will increase dramatically over the coming decades under pressure from population growth and mobility, economic development, international trade, urbanization, dietary diversification, cultural and technological changes and climate change. As demand increases, competition for resources increases with unpredictable impacts on livelihoods and the environment. Progress in developing ways to improve policy coherence and coordination between the water and water consuming sectors, including agriculture and energy, and their relevant stakeholders has been limited. The behaviors of the various actors in sectors lack of cross-sectoral policy coherence and integrated decision-making often comes at high economic, environmental and social costs, especially for small producers and the rural poor.

Today, many governments are engaged in adapting institutional frameworks to implement coherent policies that effectively address the complex interconnections and trade-offs between water, agriculture, food production, food security and energy, while finding ways to involve diverse stakeholders to foster cross-sectoral coordination at the regional, national and local levels. In this context, the debate on the Water-Energy-Food Nexus has gained ground as a means of tackling the old challenges of interdependencies. What separates the link from the other approaches is the integration of multiple sectoral objectives at the policy level. What is often missing in the debate is practical advice on how to move from concepts to practical action, i.e how to bring relevant stakeholders together at regional, national and local levels, identify multiple and sometimes conflicting issues that should be addressed and how integration should be done in practice. This raises important questions about the socio-political context in which integration must be achieved: what must be integrated, by whom, for whom and how concretely? A key challenge for the nexus is governance: who decides what issues are handled, when and how. Managing the link therefore requires focusing on institutional and social processes, and power relations. This paper is an opportunity to learn from Morroco's experience and discuss concrete ways to move from concepts to practical action on Nexus and to develop innovative strategies, policy measures and governance arrangements for the coherence of policies for sustainable development.

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Introduction

The 2030 Agenda and the Sustainable Development Goals (SDGs) have ignited a global conversation about the intricate connections among various sectors, prompting the need for enhanced coordination, cooperation, and cross-sectoral policy coherence to achieve sustainable development goals. This paper examines the significance of the Nexus approach, focusing on the interplay between water, agriculture, and energy—three pivotal sectors for poverty reduction and sustainable progress.

The Nexus Approach is framing different Interconnected Sectors. It has emerged as a vital tool for policymakers, providing a framework to comprehend and link various sectors. It facilitates aligning policies to ensure sustainable development. While this approach has successfully highlighted the challenges of sustainability and the interconnectedness of sectors, its practical governance remains a challenge (Figure 1).

The complex interconnections between water, agriculture, energy, and ecosystems underscore the necessity of a thoughtful Nexus approach.

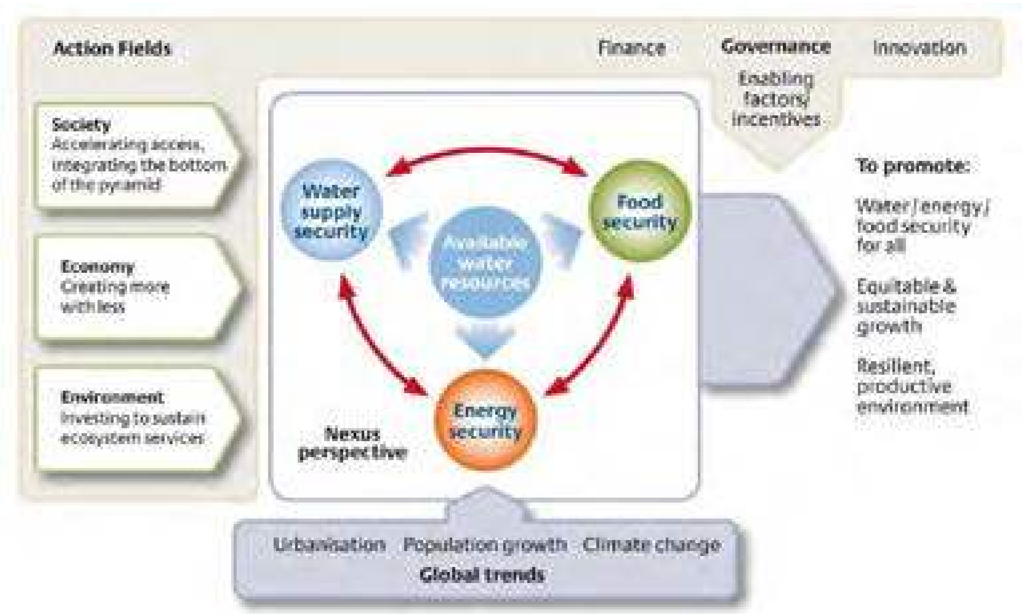

Figure 1. The water, energy, and food security nexus (*Source: Youssef Almulla et al. 2022)*

Global projections indicate an imminent surge in demand for water, energy, and food due to factors such as population growth, urbanization, economic development, and climate change. This escalating competition for resources could have far-reaching and unpredictable impacts on both livelihoods and the environment, underscoring the urgency of coherent policy responses.

Despite the diversity of agricultural landscapes that characterizes the Near East and North Africa (NENA), the region is facing common water-related challenges. Water scarcity is a particular concern, with many areas facing severe shortages of water for agriculture and food production. The per capita availability of renewable water resources in the region declined by nearly 75 percent between 1962 and 2017 and is projected to further decline by 2030 and again by 2050.

Moreover, increasing rates of groundwater abstractions have led to overexploitation of aquifers throughout the region, causing salt intrusion, groundwater pollution and a decline in water levels, all leading to overall groundwater stress[2].Water scarcity is due to several factors, such as demographic growth and the related increase in food demands, urbanization, energy

[2] FAO. 2022. The State of Land and Water Resources for Food and Agriculture in the Near East and North Africa region – Synthesis report. Cairo. https://doi.org/10.4060/cc0265en

demand and overall socioeconomic development. Besides, NENA is one of the world's regions predicted to be most affected by climate change, exacerbating water scarcity. An increase in mean temperatures, floods and droughts affects smallholders the most, as well as poorer populations with low capacities to adapt and populations experiencing conflict[3]. Water pollution and degradation of water quality also pose significant challenges in the region, affecting water availability and quality for all the uses. In the region, agriculture is a main contributor and casualty of water scarcity and pollution.

In the light of the projections in the Region, one of the key challenges to be considered is the issue of policy coherence and coordination between water and its consuming sectors, especially agriculture and energy that remain inadequately addressed. The disconnect often stems from disparate political priorities within these sectors, resulting in substantial economic, environmental, and social costs, disproportionately affecting marginalized communities.

This paper emphasizes the pressing need to address current governance gaps by integrating institutional and governance mechanisms that can harmonize diverse water needs, particularly in agriculture and energy, while catering to different stakeholder perspectives. This is crucial in the face of water scarcity and the impacts of climate change is well illustrated in the FAO conceptual framework[4]. This paper reflects on the Moroccan's experience (in the Souss-Massa region) and discusses concrete ways to move from concepts of the WEF Nexus to practical actions to develop innovative strategies, policy measures and governance arrangements for the coherence of policies for more sustainable uses of the resources.

Morocco and Souss Massa Region: Local and National context

Figure 2. Souss Massa Region (Source : Royaume du Maroc, Ministère de l'Intérieur. 2015)

The Souss-Massa province (Fig.2) is situated in the middle-western part of Morocco on the Atlantic Ocean. It has a total surface area of 27,000 km^2 and is home to 2.56 million people. The Souss-Massa region is among the top Moroccan agricultural zones as it produces 85 % of the vegetables and more than half of the exported citrus. A large part of the agricultural land is dedicated to the production of crops, including cereals, citrus, almond trees, and vegetables.

[3] Ibid

[4] https://www.fao.org/land-water/water/watergovernance/waterfoodenergynexus/en/

Therefore, about 50 % of the region's workforce is employed by the agriculture sector (the other employing sectors are tourism and fishing).[5]

Water resources are central for almost every socio-economic activity in Souss-Massa. Irrigation represents around 94 % of total water demand and the remainder goes for industry, tourism and municipal uses. Groundwater aquifers supply about 70 % of the total demand. In addition, the region has 8 large and 16 small dams to control and store the surface water that is used for irrigation, drinking, industrial and protection purposes. In terms of energy, Morocco is a net import country as it relies on coal, oil and gas imports for most of its energy needs. In particular, the Souss Massa region relies on the national grid and electricity generated in the power plants outside the basin to meet its demand as none of the dams mentioned above is used for electricity generation. The use of heavily subsidized butane for groundwater pumping in the area is adding an enormous burden on the government's budget.[6]

In Morocco, despite a modern political and legal framework, water resources are becoming increasingly scarce due to natural factors and the effects of climate change, inadequate water availability as well as a rapid increase in demand for water to meet domestic, touristic, industrial, and agricultural needs.

In the region, overexploitation of the groundwater resource and low rainfall levels is constantly reducing the water table levels of the aquifer. The water deficit in the Souss-Massa aquifer has been estimated at -188 Mm^3 in 2021. This deficit will reach -197 Mm^3 by 2050 if the management of water resources is not improved. To address this situation, an integrated development plan for the 2021-2050 period has been drawn up, focusing on six major areas (Box 1). These actions are designed to reduce the deficit to -62 Mm^3 by 2035 and a surplus of 62 Mm^3 by 2050. The plan will be implemented by the local agency of hydraulic basins in partnership with the regional office of agriculture, farmer's associations, and several other bodies in charges of irrigation and drinking water.

BOX 1 – SIX AREAS OF INVESTMENTS FOR THE SOUSS MASSA

1. Mobilization of surface water through the construction of dams and hydraulic works,
2. Desalination of sea water,
3. Reuse of treated wastewater,
4. demineralizing brackish water
5. conversion to localized irrigation, and
6. improving network efficiency

At national level, the revised version 36/15 of the Water Act 10/95 aims to improve the coordination of stakeholders in the water and its consuming sectors through the creation of a policy area to address the link between water policies and agricultural policies. Despite these efforts, the policy analysis conducted at national level within the 'Implementing the 2030 Agenda for water efficiency, productivity and sustainability in NENA countries' (WEPS NENA)[7] regional project, featured that there is still no logical framework of results to be achieved, and the existing councils and committees do not meet regularly and suffer from a lack of communication. Furthermore, the analysis revealed policy inconsistencies between water and agriculture (with incentive for agricultural productivity and borehole drillings), between land and water (with land fragmentation, inability to equip very small plots with localized irrigation, increasing number of tenants on the land, and digging of new boreholes because the access to land is coupled with access to water) and between water and energy (with the existence of a butane gas compensation system for water use).

Resource management remains fragmented in most cases and lacks effective coordination mechanisms, leading to a sectoral approach to policy planning and fragmented development strategies and policies. This fragmentation and lack of intersectoral governance mechanisms advocates for the need of a transformative shift in the approach of public policy development

[5] Youssef Almulla, et al. 2022
[6] Ibid
[7] https://www.fao.org/in-action/water-efficiency-nena/es/

from "silos" to the NEXUS approach to minimize inter-vulnerabilities and strengthen synergies between the water, energy and agriculture sectors.

Morocco's Leadership in Nexus Governance

Many governments in the Near East and North Africa, including Morocco, are taking proactive steps to adapt institutional frameworks that foster coherent policies. Morocco's experience in the Souss Massa region provides valuable insights into bridging sectoral gaps and achieving cross-sectoral coordination.

The region has demonstrated remarkable strides in integrating its water, agriculture, and energy sectors and aligning their regional strategies and plans. Through innovative policies and cross-sectoral collaboration, the Souss Massa actors have managed multisectoral dialogues around evidence and the scenarios provided by an integrated model on ways to balance the water requirements of agriculture and energy aiming for sustainable resource management.

For instance, a careful review of energy consumption in agriculture revealed that energy counts for about 25% of the production cost. Electricity and fossil fuels represent respectively 70% and 20% share of the total energy consumed in agriculture. The scenarios also looked at the implication of the modernization of agriculture with drip irrigation systems increasing water efficiency but often also increasing irrigated areas so leading to an increase in water use. Around 71% of the total irrigated area has been converted to drip irrigation in the Souss Massa area. This has generated an annual water savings estimated at 180 Mm^3. The introduction of solar irrigation promoted by the energy sector to cut on butane consumption is a promising option provided it is introduced with boundaries on the quantities of water pumped and the irrigated area cultivated. If done with the right set of limits and a monitoring/control system, this approach can help align agricultural water consumption and energy use with broader water conservation goals, promoting a harmonious relationship between water use in agriculture and energy production.

In terms of governance model, the results of a region-wide dialogue involving public bodies, the private sector and civil society, showed a consensus for a shared governance model. A number of concrete actions and projects were proposed to ensure a smooth transition from the existing model (sectoral governance in silo) to the new model. The objective in short and medium terms is to improve interactions between partners in order to collectively manage inter-vulnerabilities and exploit synergies.

From Concept to Action: Practical Steps

While the Nexus approach has gained power in theoretical discussions, translating it into practical action remains a challenge. There is a need for pragmatic guidance to bridge the gap between theory and action, bringing stakeholders together at various levels to identify and integrate conflicting issues, ensuring effective cross-sectoral coordination (Figure 3).

Converting the theoretical underpinnings of the Nexus approach into actionable strategies necessitates a well-defined roadmap.

While the conceptual value of this approach might be evident, municipal officials might struggle with the practical execution. This is where the proposed practical steps come into play.

- The first step focus on understanding the decision space –a rapid assessment of legal and institutional framework is done..
- The second step involves creating a comprehensive inventory of stakeholders. This includes representatives from sectors related to water, energy, and food security, as well as other relevant sectors like environment, agriculture, and urban planning. Bringing together these diverse stakeholders lays the foundation for inclusive discussions.
- Once the stakeholders are identified, a careful review of sectoral issues and resources flows is carried out in a third steps.

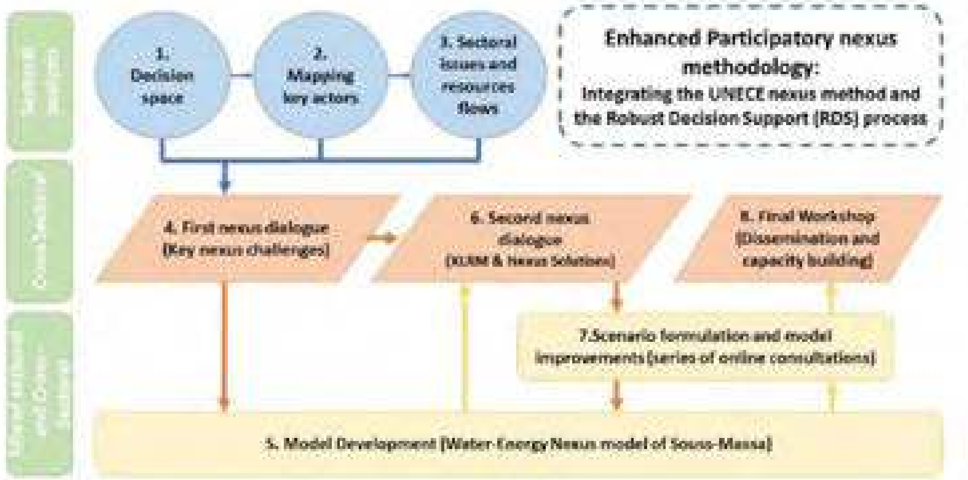

Figure 2. Schematic diagram of the enhanced participatory nexus methodology. (Source: Youssef Almulla, et al. 2022)

- With a good understanding of the decision space, the stakeholders and issues, the next steps revolves around organizing a series of multi-sectoral workshops. These workshops serve as platforms for dialogue, where experts from different fields can articulate their concerns, priorities, objectives. They will also discuss the area of vulnerability and the possible interventions. By fostering open conversations, potential conflicts and synergies can be unveiled, forming the basis for effective coordination.

  To illustrate, imagine a Nexus workshop attended by water resource managers, energy experts, and agricultural specialists. In this setting, water managers might express concerns about the potential energy-intensive processes involved in water treatment, which could impact overall energy availability. Simultaneously, agricultural representatives might highlight the dependence on both water and energy resources for irrigation systems. While the energy specialists raise their concern on the weight of pumping for water or irrigation on the energy grid or on fuel or butane creating greenhouse gases and distorting energy support policies for poor families (ex. At the time of this study, Butane in Morocco was subsidized for low income household and this is a significant cost for the government diverted to irrigation). Through guided discussions, these stakeholders can recognize the intricate dependencies and conflicts, paving the way for collaborative solutions.

- Along the process, the integrated model is developed, reviewed and validated. Scenarios are also tested and developed in a collaborative manner identifying common goals, risks and shared benefits. This involves pinpointing areas where the interests of different sectors align. For instance, in our scenario, all stakeholders might agree that optimizing water productivity producing more outputs with less water in the same irrigated area (multiple actions are involved including good agronomic practices, irrigation scheduling, improved irrigation systems etc) but also reduce energy demand. Identifying these win-win situations creates a strong incentive for cooperation.

- Following this, the last step entails devising an integrated action plan. This plan outlines specific projects, policies, or interventions that address the identified conflicts and leverage the synergies. Returning to our example, the integrated action plan might propose the implementation of smart irrigation systems that reduce water consumption in agriculture, subsequently leading to energy savings, considering climate change effects in the choice of crops and tools.

- Lastly, continuous monitoring and evaluation form the basis of review. Regular assessments of the implemented actions allow for adaptive management. If, for instance, the smart irrigation system results in unforeseen energy consumption patterns, adjustments can be made promptly, ensuring the sustainability of the Nexus approach.

The transition from conceptualization to practical implementation of the Nexus approach demands a structured series of steps. These steps not only to guide stakeholders in recognizing the complexities and opportunities within the Nexus framework but also empower them to collaborate effectively across sectors. Through real-world examples and targeted action plans, the Nexus approach can evolve from an abstract concept to a potent tool for addressing the challenges of our interconnected world. Consider a scenario where a local government aims to adopt the Nexus approach to address the interconnections between water, energy, and food security. The Souss Massa Nexus followed the dialogue process illustrated in Figure 4 and broaden its scope at the end when thinking of the way to make it sustainable.

FAO, in collaboration with the Stockholm Environment Institute (SEI) and KTH Royal Institute of Technology in Stockholm have been working on the WEF Nexus component of the regional WEPS NENA project, where this component aims to make visible complex tradeoffs between the natural resource dependencies of energy, food and water systems, and environmental threats including biodiversity loss, climate change and localized air and water pollution. The approach combines methods from the United Nations Economic Commission for Europe (UNECE) and robust decision support.

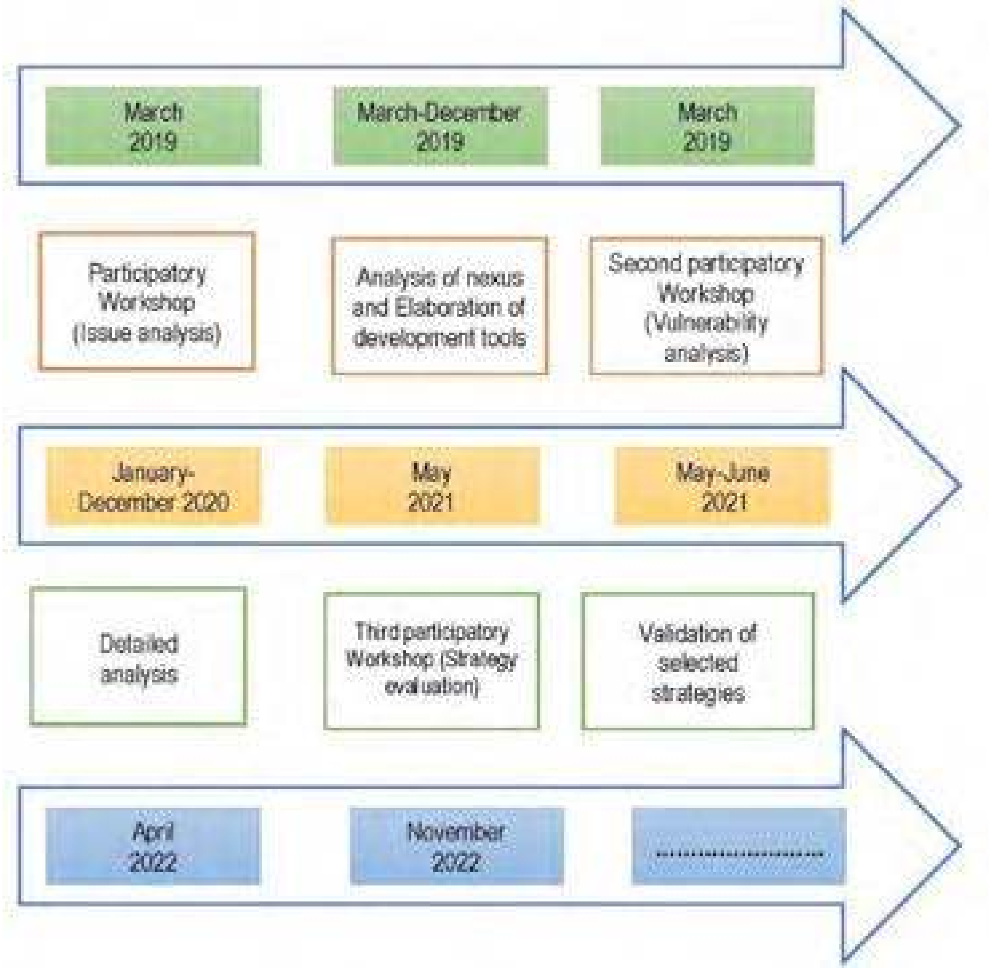

Figure 3. The Nexus dialogue in Souss Massa (*Source: authors)*

In Souss-Massa, three Nexus dialogues were held (Figure 4): the *First 'Nexus Dialogue'* - **Assessing Water Sustainability using a Water-Food-Energy-Climate-Ecosystems Nexus analytical framework** was conducted in April 2019, followed by the analysis and the development of modeling strategy in consultation with the different Nexus-related potential stakeholders in the country. The *Second 'Nexus Dialogue' - Hand on NEXUS analysis was held* in March 2020, to build on the first Nexus workshop and the following consultations with the different Nexus-related potential stakeholders in the country. The main objective of this second Nexus Dialogue workshop was to present the preliminary nexus model results that illustrate the tradeoffs and potential synergies in developing policies and infrastructure to increase the overall water-energy-agriculture co-management for resilience. The goal is to inform decisions particularly in the context of various scenarios including climate change that could cause increased vulnerability for the Souss Massa in Morocco. The workshop engaged key actor groups – experts, resource managers, policy-makers, and stakeholders involved in the governance of water, agriculture and energy, with the results around integrated solutions for sustainable planning in Morocco in the face of critical uncertainties identified in the first Nexus Dialogue. The stakeholders also provided ideas about how to improve the models, and give feedback about possible new nexus strategies.

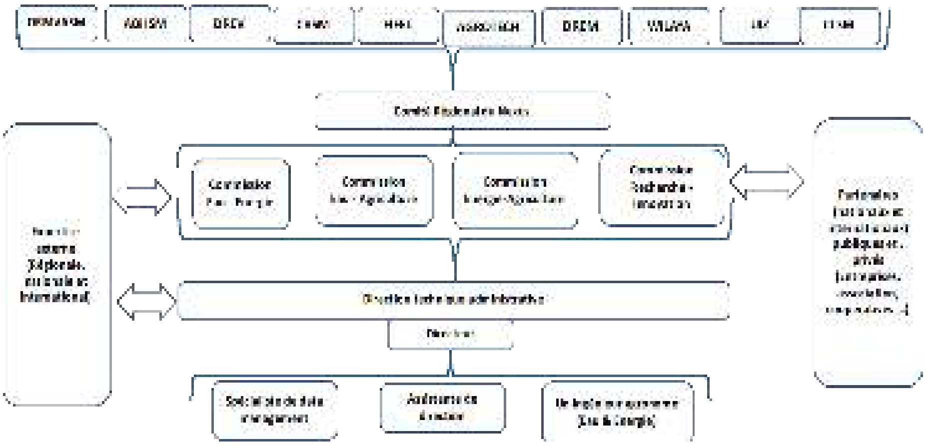

Figure 4. Development of a nexus governance mechanism.
The acronyms indicate different public bodies in Morocco working at regional level.
Source: authors

Through this series of dialogues four nexus challenges were identified (Figure 5) in Souss-Massa region. These include (1) water scarcity as a result of over-pumping of aquifers to meet agriculture demand for irrigation water, (2) the use of grid electricity and Butane gas as the main sources of groundwater pumping which comes with serious economic and ecological burden, (3) the relatively low valuation of irrigation water and (4) the degradation of the quality of water and the need of desalinization. A number of Nexus solutions were proposed including the improvement of water supply through a better management of surface water mobilization, sea water desalination, saline water demineralization, recycling if waste water, agriculture water productivity and butane gas phase-out via solar energy.

The third dialogue was held on 15 May 2021 and gave the opportunity to discuss the sustainability of the Nexus dialogue at the Souss-Massa level. It led to a proposal to create a regional structure responsible for implementing the Nexus. It was also combined with a technical training on the model and its interface.

The workshops enabled a dynamic dialogue to be established around the independence and interdependence of the three sectors and has generated concrete solutions such as the creation of a modelling platform, which has been online since 2020[8], and the completion of three regional studies: water accounting, water productivity and energy consumption in the agricultural sector.

Governance and Decision-making in Nexus Management

Effective governance is pivotal to managing the Nexus approach. Decisions about which issues to address, who makes these decisions, and how they are implemented all shape the outcomes. The Nexus approach highlights the significance of focusing on institutional processes, social dynamics, and power relations to establish successful governance structures. FAO proposes a structured method to analyze water governance and explore the interactions with other sectors. (REF water governance analysis methodology).

[8] https://souss-massa-nexus.herokuapp.com/

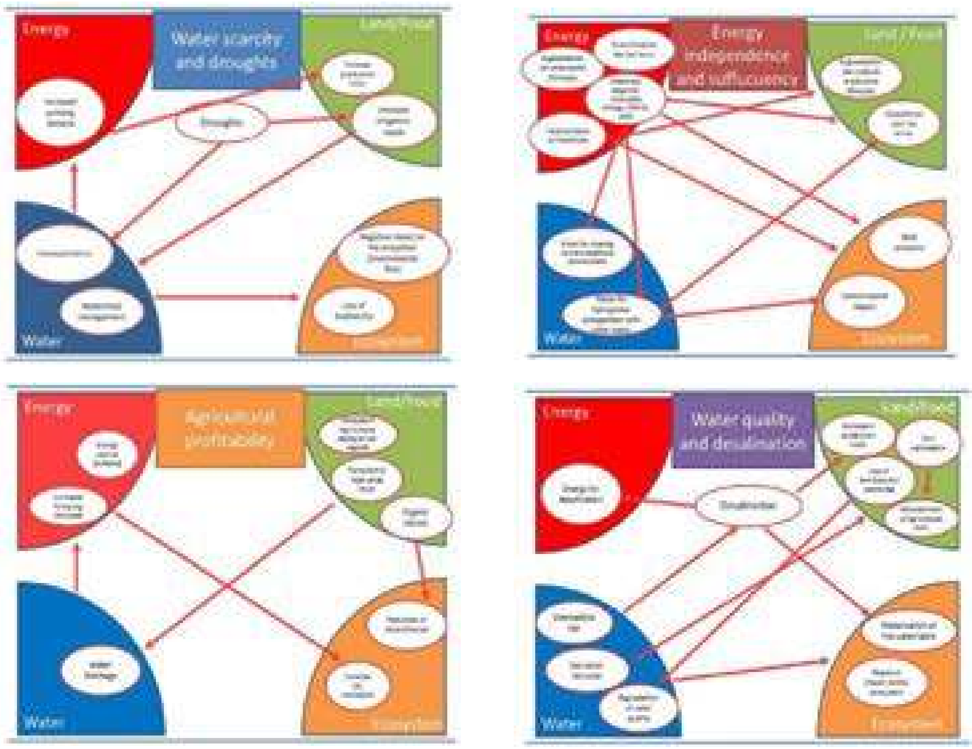

Figure 5. Mapping the Nexus challenges (**Source:** Youssef Almulla, et al. 2022)

In a world characterized by interconnections between various sectors, the Nexus approach has emerged as a holistic framework for addressing complex challenges at the intersection of water, energy, food, and environmental sectors. However, successfully managing the Nexus approach requires more than just acknowledging these interlinkages; it necessitates robust and well-thought-out governance mechanisms. Effective governance is the prerequisite that determines the success or failure of the Nexus approach, as it shapes decisions, implementation strategies, and ultimately, the outcomes.

- Decisions- The heart of effective governance in the Nexus approach lies in the decisions made about which issues to prioritize. With multiple sectors in play, each with its own set of challenges and opportunities, selecting the most pressing concerns requires careful consideration. A well-structured governance system brings together stakeholders from diverse sectors, enabling them to collectively identify and prioritize the most critical issues. This participatory process ensures that decisions are grounded in a comprehensive understanding of the interconnected challenges, leading to more effective allocation of resources and efforts.
- Lead- Central to successful governance within the Nexus approach is determining who holds the authority to make crucial decisions. The involvement of government bodies, non-governmental organizations, businesses, and local communities in decision-making processes is pivotal. A balanced distribution of decision-making power prevents any one group from dominating the agenda. This inclusivity not only enhances the quality of decisions but also fosters a sense of ownership and shared responsibility among stakeholders.
- Implementation strategy- Even the most well-crafted decisions are futile without effective implementation. Governance mechanisms play a pivotal role in translating decisions into actionable strategies. Collaborative efforts across sectors, driven by transparent communication and coordination, are essential for successful implementation. Furthermore, clear delineation of roles and responsibilities ensures that actions are aligned, minimizing duplication of efforts and maximizing the efficient use of resources. The success of governance structures in the Nexus approach is

intertwined with the functionality of institutional processes. Institutions provide the framework within which decisions are made and actions are taken. Strengthening these institutions requires fostering a culture of cooperation, accountability, and adaptability.

- Power dynamics- Additionally, recognizing and addressing existing power dynamics is crucial. Often, imbalances in power can hinder effective decision-making and implementation. Striving for equitable representation and empowering marginalized voices helps rectify these dynamics, leading to more robust and inclusive outcomes. Power relations play a subtle yet influential role in governance. Successful governance of the Nexus approach necessitates a deep understanding of these dynamics and their potential impacts on decision-making processes. Addressing power imbalances ensures that decisions are not swayed by vested interests and that outcomes benefit the broader community. Transparent discussions, conflict resolution mechanisms, and mechanisms for grievance management all contribute to a more equitable governance structure.

Proposed governance structure in Morocco for Nexus

In the Souss-Massa region a nexus body was proposed for the management of the nexus program (Figure 6): a steering regional nexus committee (RNC), four thematic commissions (commission Water-Energy, commission Water-Agriculture, commission Energy-Agriculture and commission Research-Innovation) and one executive body (Technical and administrative Department, DTA). The RNC will be responsible for outlining the strategic orientations of the Nexus. Technical commissions have the task of identifying and developing concerted projects and actions using the Nexus approach. Theses commissions will be chaired by members appointed by the RNC. The implementation of the action plan drawn up by technical commissions and approved by the CRN may be entrusted to the nexus executive body.

The thematic commissions and the DTA will have to interact with national and international experts in the fields of water, energy and biodiversity, and forge partnerships with private companies, non-governmental organizations, civil society, and international bodies.

As for legal status, the Nexus can start as a flexible structure, designated by a Gubernatorial Decree, chaired by the Wali or the President of the Region and steered by the Souss-Massa Regional Agricultural Development Office, which will provide the Secretariat. The structure may gradually evolve towards a more “solid” form in the status of a Public Interest Grouping or even a Public Private Partnership. The legal form must be the subject of consultation with experts.

The Nexus governance body can be financed through state subsidies, subsidies from local authorities, in particular the Regional Council, payments for services and aid funds from international organizations.

To wrap up, the Nexus approach presents an innovative way to tackle complex challenges, but its success is contingent upon effective governance. By addressing issues of decision-making, authority, implementation, institutional processes, and power relations, governance structures can be established to drive the Nexus approach toward its desired outcomes. It is through thoughtful and inclusive governance mechanisms that the intricate web of interconnections inherent to the Nexus approach can be effectively managed and navigated, ultimately leading to a more sustainable and prosperous future.

Conclusion

Paving the Path Forward

The impending surge in resource demand necessitates a paradigm shift towards a more holistic and interconnected management approach. As global challenges mount, a coherent Water-Agriculture-Energy Nexus approach becomes increasingly vital. Learning from examples like Morocco's, the international community can chart a course towards effective policy coherence and cross-sectoral coordination. This investigation underscores that while the Nexus debate has sparked awareness, practical action remains the missing piece. By exploring Morocco's successful experiences and focusing on governance mechanisms, the world can move beyond discourse and take real strides toward policy coherence for sustainable development.

In essence, the escalating competition for water, energy, and food underscores the imperative of the Water-Agriculture-Energy Nexus approach. As this nexus becomes more pronounced in the face of evolving challenges, proactive measures must be taken to align policies, bridge sectoral divides, and ensure a sustainable future for all.

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THE USE OF SOLAR STILLS IN AGRICULTURE: SUSTAINABLE IRRIGATION AND FOOD PRODUCTION

Souad Nasrdine[1], Mohammed Benchrifa[2], Jamal Mabrouki[3]* and Miloudia Slaoui[1]

ABSTRACT

Water, energy, and food are unquestionably necessary for the life of all living creatures. These resources are frequently linked together, and their intimate connections have a big impact on how we conduct our daily lives. However, millions of people around the world are suffering from water shortage, which has become a real threat. Whereas water, unlike other raw materials, has no possible alternative. It is an essential factor in the germination of food plants, in energy production and for the sustainability of human life. Solar distillation combines water supply and energy conservation, and if this water is used for irrigation, it will also ensure food supply. This study proposes an automated solar distillation system for agriculture using solenoid and sensors to monitor the system remotely.

Keywords: Solar still, water shortage, energy conservation, irrigation.

1. INTRODUCTION

Water, energy and food are essential for human life but with the increase in world population it has become difficult to provide these three elements (Isaías et al. 2019). Water resources are decreasing at an alarming rate, especially in regions that suffer from lack of rain and scarcity of surface and ground water, plus climate change and increased pressure from economic and agricultural activities that require a lot of water and aggravate the lack of water resources (El-Awady et al. 2014). The scarcity of freshwater resources is jeopardizing Morocco and other Mediterranean countries. Today, farming has become impossible in areas that were once farmland, and the nightmare of drought year after year became a reality, hence the need to find alternative solutions to meet the need for water and food with less energy (Bekhet & Abdullah 2010). In this case the use of renewable energies remains the best solution (Wazed et al. 2018). The principle of sustainable irrigation is based on the optimal use of water in an efficient, environmentally friendly and economically viable way, while maintaining long-term agricultural productivity (Kelley et al. 2010). It aims to preserve water resources, reduce waste and reduce harmful effects on communities and ecosystems. There are several ways to save water and prevent water deficit, such as rainwater harvesting and wastewater reuse to reduce pressure on groundwater and other natural water sources, solar desalination is an excellent example of clean technology for water efficiency and control (Sampathkumar et al. 2010).

It consists of separating impurities from water using the principles of evaporation and condensation. The contaminated water is poured into a shallow basin made of materials that can effectively absorb solar radiation during this process. When the sun light hits the basin, the water heats up and begins to evaporate. The water vapor rises, leaving impurities and pollutants behind, then condenses on a cooler surface, such as a glass lid or a collecting tube. The condensation forms droplets which are collected as purified water (Singh et al. 2020). In this study an automated solar distillation system with solenoid valves and sensors is proposed in order to meet the need for food production and sustainable irrigation while conserving energy and water.

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2. BACKGROUND

Agriculture ensures the need for food security. Most of the agricultural machinery is dependent on energy resources (Assalaou et al. 2017) and mostly runs on fossil fuels (García et al. 2020), leading to increased greenhouse gas emissions and accelerated climate change. The modernization of many agricultural production operations, such as irrigation, contributes in part to this dependency (Velasco-Muñoz et al. 2019). Irrigation is mainly used to provide controlled water to crops when rainfall is not sufficient to meet the crop water demand and water can then be extracted from surface reservoirs or aquifers (Pardossi et al. 2009). Several solutions have been proposed to solve the problem of water shortage while preserving energy (Mehta et al. 2011). Researchers tried to use a non-conventional water recourse, sea water or brackinsh water and use a less expensive form of energy, in the form of solar energy. Based on their energy supply, solar stills are classified into two categories: passive solar stills and active solar stills, active solar stills produce more heat energy for faster evaporation. An additional source of thermal energy can come from a solar collector (Abdessemed 2023) or any residual thermal energy available from any industrial installation (Sadi 2000). However, conventional passive solar stills use solar energy as the only source of thermal energy, e.g., inclined plane (Kumar et al. 2000), cascade solar still (Headley 1973), wick solar still (Alawee et al. 2021), spherical still (Attia et al. 2021) and vertical solar still (Lim et al. 2022).

METHODS

2.1 The solar resources of the study area

The city Rabat, the capital of Morocco, is located on the Atlantic coast, in the region of Rabat-Salé-Kénitra.The climate of Rabat is Mediterranean, with mild and rainy winters and hot and sunny summers, it has a good solar resource according to several studies and solar radiation forecasts, the angle of incidence of solar radiation is taken into account, which depends, among other things, on the declination, the latitude, the inclination and the hour angle (Ouammi et al. 2012).

2.2 Solar stills

The system is composed of an inclined zinc plate which plays the role of an absorber, it is corrugated in order to ensure the uniform distribution of water on the absorption surface and an ordinary glass cover of 4 cm thickness that acts as a condenser. The filling of the metal tank is carried out by gravity. The distillate is collected in the gutters located at the end of the roof as shown in Figure 1.

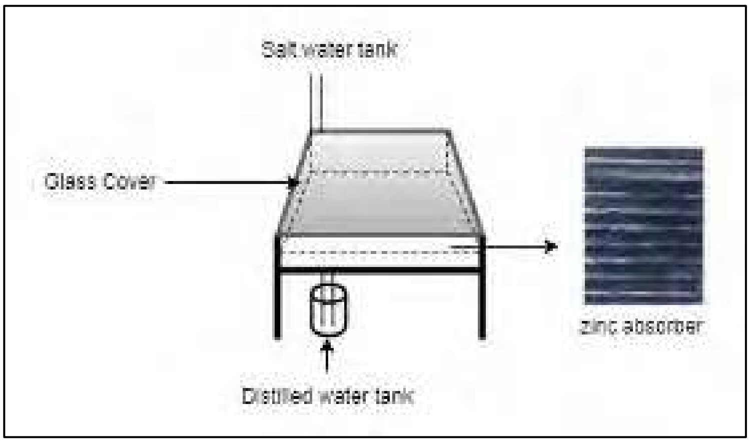

Figure 1. Diagram of operation of the tilted solar still

The inclined solar still works in a simple way. It is based on natural evaporation and condensation processes. The distiller uses sunlight to heat the contaminated water, which then evaporates leaving behind impurities. The steam condenses on the inclined glass plates and flows down to collect the purified water in the channels.

3. RESULTS AND DISCUSSION

3.1 Solar radiation

The weather forecast is taken into account in the calculation of solar radiation, since, for example, on a cloudy day we would only have diffuse radiation, much less than direct radiation. Figure 2 shows the variation in solar radiation at Rabat city.

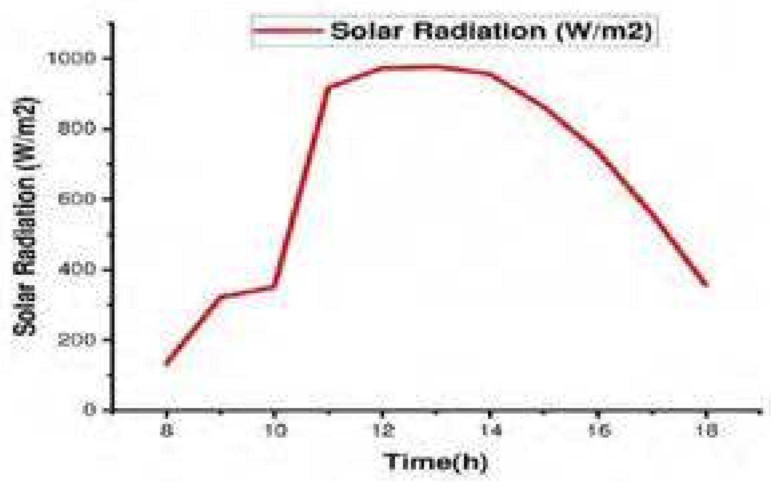

Figure 2. Variation of solar radiation as a function of time on May 15, 2022 in Rabat.

Test day, May 15, 2022, was a sunny day. The sun rose at 6:23 a.m. and set at 8:26 p.m. The figure shows that the city of Rabat receives a fairly significant amount of solar radiation energy.

The principle of irrigation

The development of a new irrigation modality is planned, due to the shortcomings qualifying the traditional irrigation practices, where the water consumption turns out to be inpractical, because timers in force operate according to fixed schedules previously recorded and therefore, can not be adapted to differences in humidity, temperature, ventilation and sunshine. Using sensors, it will take into account the luminosity and moisture content of the soil, making it possible to detect the need for water of the plants and to manage the irrigation according to the time and duration of irrigation as well as the flow rate of water to be used. The block diagram is shown in Figure 3.

The irrigation systems are mainly composed of a surface pump controlled by a program and connected directly to the tank of the solar still shown in Figure 3. The water is pumped into two fields to be watered using a pump equipped with two solenoid valves. Both fields have soil moisture and light sensors. These sensors provide information to the program which triggers the automatic opening or closing of the solenoid valves.

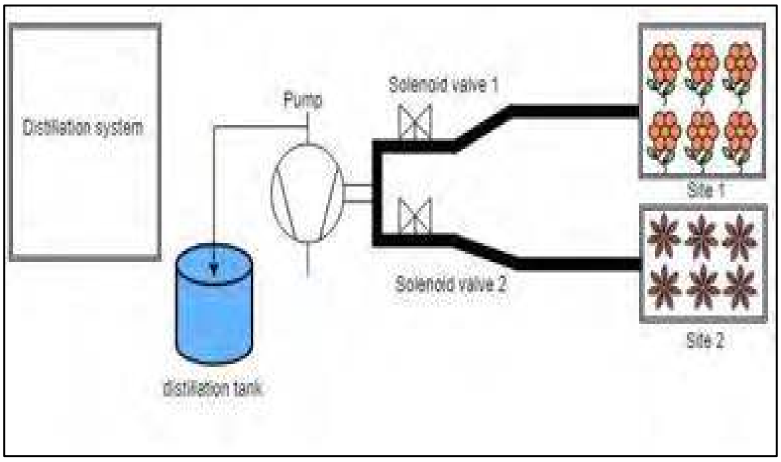

Figure 3. Schematic diagram of irrigation using distilled water.

Description of the block diagram

The block diagram of the irrigation system basically consists of three parts, as shown in Figure 4. In addition to the power supply, these components include: a board containing a measurement unit using sensors, a processing and control board, a system containing the actuators equipped with indicators.

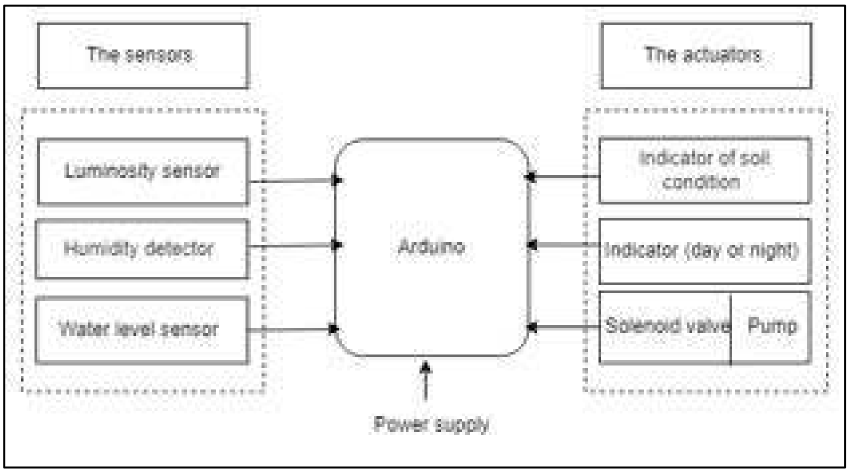

Figure 4. Block diagram of the system.

Humidity, light and water level sensors are part of the measurement unit. The former is responsible for measuring soil moisture. Brightness sensors are used to prevent the pump from running during the day. Regarding the level sensors, they are used to identify the presence of water in the basin before the start of irrigation. A photovoltaic panel supplies these three sensors.

Figure 5 shows the flowchart summarizing the operating program of ordinary irrigation.

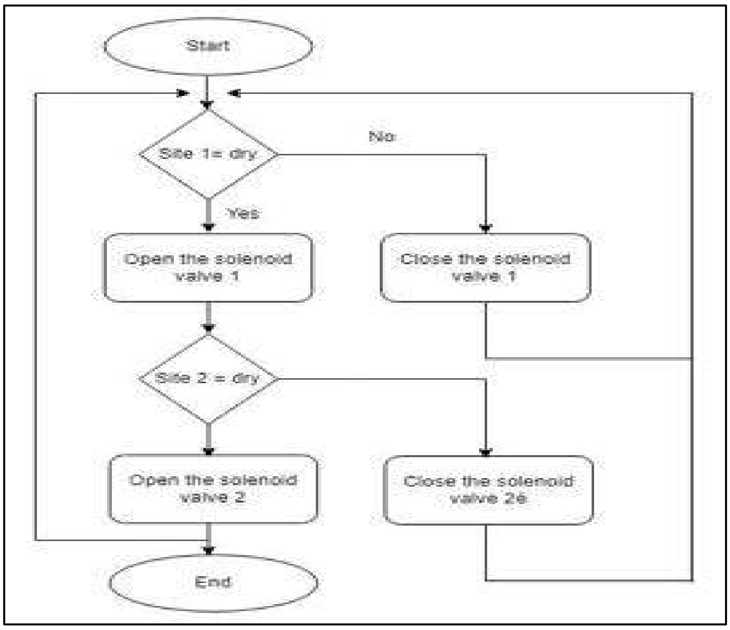

Figure 5. Automatic watering diagram.

The number of fields to be irrigated may be more than two. In this case, for n given fields, n solenoid valves can be added.

4. CONCLUSION

Energy and water and food in the world are inextricably linked. With increasing population and food demand, water scarcity could threaten the long term viability of energy projects and food production which will hamper development. Promoting renewable resources in water supply such as solar, wind, biomass, and tidal, geothermal, small-scale hydropower can alleviate the water deficit. The agricultural industry has enormous potential with these renewable resources, it is possible to see the importance of renewable energy for small-scale irrigation, especially in arid and semi-arid areas. The study focused on an inclined solar still with a zinc absorber combined with solenoid valves and sensors to ensure sustainable crop irrigation.

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WATER - FOOD - ENERGY NEXUS IN EGYPT

Zeinab Hussien BEHAIRY[1]

ABSTRACT

In the coming decades, the world will be facing severe challenges in terms of water, energy and food due to the increased water use, increased energy demand, increased food demand and changing diets. Those challenges are expected to be amplified due to the effects of climate change. Egypt is a country doing its best to achieve water, energy, and food security, which are key issues in achieving sustainable development.

Egypt is facing major challenges regarding the prospects of population growth, climate change threats, and geopolitical factors, which are all affecting the availability of resources such as water, energy, and food. Various sectorial plans are being put in place to achieve resources security and sustainability. However, policies in one sector might affect other sectors, thus the nexus approach is employed to capture the interdependencies.

The relevant state institutions in Egypt faced the problems of secured water, food and energy sources by applying modern irrigation systems, lining canals, developing non-conventional water resources, limiting the areas of water-consuming crops such as rice, sugar cane and bananas, as well as expanding the areas of renewable energy in several regions across the country, and using modern scientific and technological methods to achieve the goals of the Nexus.

Keywords: Water-Food-Energy Nexus, Adaptation strategies, Climate change impact, Egypt.

INTRODUTION

The majority of Egypt's territory is desert, and the country's inhabited land area, concentrated along the River Nile, comprises only 7.8% of the total area which is 1 million km² as illustrated in Figure 1. **(Simon A. Mason, 2005)**

Fig. 1. Projected water scarcity in the Nile Basin countries for the year 2025 (Simon A. Mason, 2005)

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Annual population growth is high at 2.5%, putting pressure on a slowly growing water supply. 97% of the water resources originate from outside Egypt's borders, making the supply highly vulnerable and sensitive to any uncoordinated upstream developments. Climate change would have an impact on Egypt. In the north of Egypt, rising sea levels could have a negative impact on in the Nile Delta region. In the south of Egypt, heat waves put pressure on Nile water levels and on household consumption of water.

KEY STATISTICS

According to the Ministry of Irrigation and Water Resources, Egypt needs more than 114 Bm^3 of water supply each year to have full self- sufficiency to cover demand from agriculture, industry, and household consumption. However, only 60 Bm^3 is available each year, creating an annual water deficit of 54 Bm^3. **(Mohamed Abdel Atty, 2018)**

The deficit is covered by:

- Importing water-intensive crops such as rice and wheat:
  - Egypt is one of the biggest importers of water-intensive crops in the world.
  - These imports save more than 34 Bm^3 of water each year.
- Water recycling/reuse:
  - Represents 33% of annual water consumption (26.4 Bm^3)
  - Egypt is the number one water recycler in Africa.
  - Water recycling is highly affected by the degree of pollution in the water. A high level of water pollution puts pressure on Egypt's water management system.

THE MAIN SOURCES OF WATER IN EGYPT

- The Nile River inflow, groundwater, as well as rainfall represent the conventional water resources in Egypt. However, seawater desalination and the use of wastewater represent the non-conventional water resources as illustrated in Figure 2. **(**Radwan G. Abd Ellah, 2020)

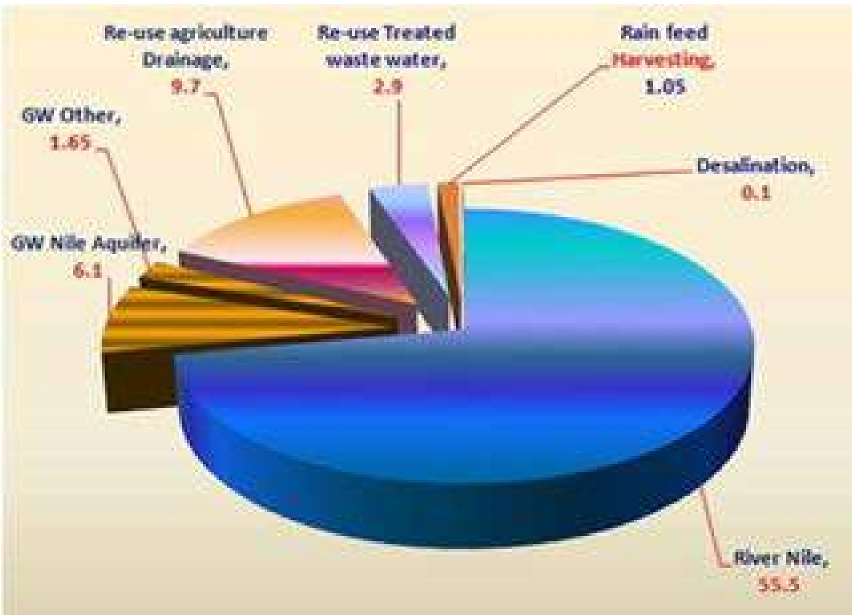

Fig. 2. Water supply in Egypt (billion m^3) (Radwan G. Abd Ellah, 2020)

- Water consumption percentage by sector in Egypt is illustrated in Figure 3. (Mahmoud Aziz, 2020)

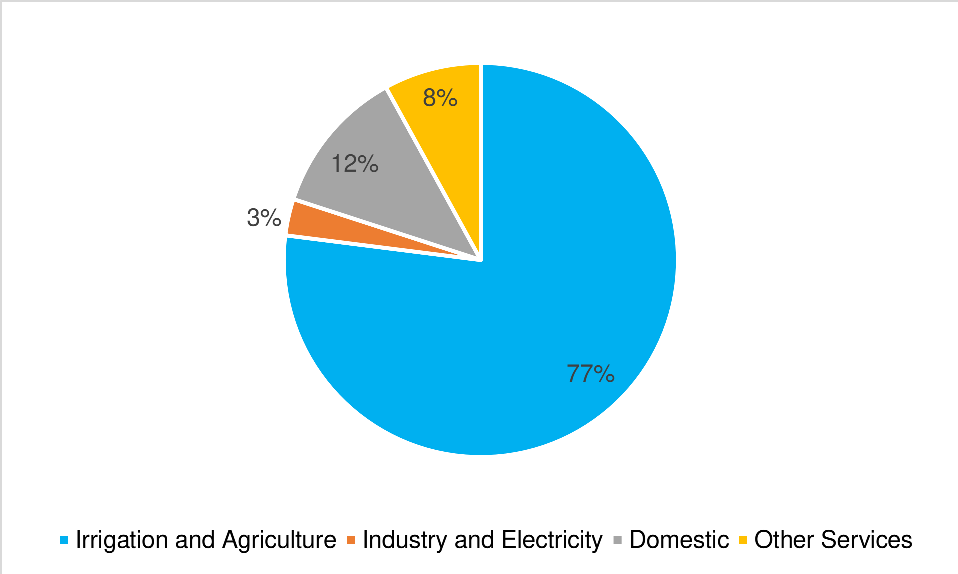

Figure 3. Egypt's Water Consumption by percentage (Mahmoud Aziz, 2020)

STRATEGY FOR MANAGING WATER –ENERGY-FOOD NEXUS IN EGYPT

The four-pillars approach to sustainability:

Pillar 1: Water	Desalination plants Fresh water harvesting and storage (from flash floods among other sources) Treating sewage water, industrial water and wastewater controlling pollution
Pillar 2: Energy	Expanding the use of solar energy in addition to hydropower Completion of the construction of the Dabaa nuclear power plant, located at Al Dabaa, Matrouh Governorate
Pillar 3: Crop	Rationalizing crop cultivation Increasing irrigation efficiency Investing in farm technology (example: a sensor was developed to measure the irrigation requirement for farmers to cut down on excessive water use) Improving water management Aggregating small land tenures into bigger areas (200+ acres)
Pillar 4: Raising Awareness	Capacity building Awareness campaigns Media coverage

WATER, ENERGY AND FOOD NEXUS ACTIONS IN EGYPT

Understanding and managing the complex interactions between water, energy and food is essential as Egypt's has limited resources that need to be used and managed sustainably.

The water, energy and food nexus according to the Food And Agriculture Organization of the United Nations **(FAO),** means that water security, energy security and food security are very much linked to one another, meaning that the actions in any one particular area often can have effects in one or both of the other areas. **(FAO, 2014)**

These three sectors (water, energy and food security nexus) are necessary for the benefit of human well-being, poverty reduction and sustainable development. Anticipation of potential trade-offs and synergies allows the design, appraisal and prioritization of response options that are viable across different sectors. **(FAO, 2014)**

Therefore, it is important to take a comprehensive look at the Inter-linkages between water, energy and food and their management in Egypt. To face water shortage in Egypt, the authorities have begun re-considering the areas of high-water-intensive crops such as rice and sugarcane and issuing instructions for each crop:

Rice

The Ministry of Agriculture has identified 7 rice varieties as strategic water-saving crops. These varieties give high productivity, resistance to disease, adapt to various water and climatic conditions, and have a short growth season, to achieve high efficiency in the use of irrigation water which saves water quantities that can be used for cultivating other crops.

In addition, the Farmers' Union is promoting the use of modern irrigation systems and cultivating dry rice varieties. The Government has also reduced rice cultivation areas by more than 30 percent. (Rehab Ismail, 2018)

Abdelhalim et al., (2017), illustrated that in case of water scarcity, application of irrigation every 12 days with 3 cm depth can be recommended because it resulted in similar water productivity value as application of irrigation every 6 days with 7 cm depth for both cultivars. The Giza178 variety can use water more efficiently and attains higher water productivity, compared to Oraby2. Therefore, it was recommended to be used under water scarcity conditions in Egypt. In all cases, legume crop was recommended to be cultivated before rice to improve soil quality and increase yield.

Sugarcane

The policy options of water saving in sugarcane production are: (1) limiting the area cultivated with sugarcane to meet only the requirement of the existing sugar factories; (2) improving on-farm water use efficiency and sugarcane productivity; (3) importing sugar. (Amer et al., 2017)

Land Management Measures. This is carried out by:

- Increasing the agricultural area by about 1.5 million acres
- Expansion of land reclamation in the south of the country and east of Owainat – New Valley Governorate, it is in a remote location in the Western Desert in the extreme south-west of the country.
- Expansion of intensive crop farming.

Increasing water-use efficiency in irrigation: This is carried out by adopting sustainable agricultural practices and promote cultivation of non-water intensive crop varieties.

Informing farmers about the modern irrigation systems: farmers should know the benefit of modern irrigation systems as opposed to the flood irrigation methods traditionally used in Egypt's cultivated land to use Egypt's limited water resources more efficiently. The benefits of modern methods of irrigation include the more efficient and more equitable distribution of water, the decreased use of fertilizers and pesticides, and hence fewer costs, and the increased productivity and competitiveness of Egyptian agricultural products.

Lining of canals: This would enhance water management and distribution, ensure the delivery of water to the ends of canals, and inhibit pollution. It is estimated that the lining project is to save 5 billion cubic meters in seepage losses. (Egypt Today, July 2021)

Using non-conventional water resources: Egypt has 146 wastewater treatment plants having a total daily capacity of five million cubic meters. (Egypt Today, April 2021)

The Ministry of Housing and Utilities pointed out that the total cost of those plants is LE* 29.5 billion (USD 957 Million), and that the cost of treating one cubic meter of water is LE* 10,000 ** (USD 325). The ministry of housing has been working on two other wastewater treatment plants. One of them is Bahr Al Bakar whose daily capacity is equal to the combined capacity of the 146 existing treatment plants. The facility is expected to treat 5 million cubic meters of water per day to reclaim and cultivate around 400,000 feddans*** (168,000 hectares) in the east of Suez Canal.

In addition, 19 desalination plants worth a total of LE* 11 billion (USD 356 Million) and whose total daily production is 550,000 cubic meters were inaugurated in February 2022. Those are built in Nabq, Ras Sidr, Abou Zanima, Dahab, Nuieba, Arish 1, Arish 2, Arish 3, Arish 4, Sheikh

Zowayed 1, Sheikh Zowayed 2, Sidi Barani expansions, western Port Said, Dabaa, Marina 1, Marina 2, Marbella, and New Mansoura.

Egypt is expected to have 65 desalination plants distributed among six governorates, these are Matrouh, South Sinai, Suez, Ismailiyah, North Sinai, and the Red Sea. The total daily production of those is expected to be 750,000 cubic meters. The projects are constructed within a strategy to increase Egypt's water resources, and secure water for irrigation. The value of the strategy – launched in 2020 - is LE* 435 billion (USD 14 Billion) and is scheduled to be accomplished by 2050. (Egypt Today, 2020

In the energy sector, the Chairman of New and Renewable Energy announced that the amount of this new clean energy generated in 2020's is 6,000 megawatts.

The breakdown is 1,465 megawatts of solar energy generated in Aswan's Benban Solar Station, 580 megawatts of wind energy generated in Hurghada's Gabal al-Zeit Wind Farm, 250 megawatts of wind energy generated in other wind farms, and 3,000 megawatts of hydropower.

The total amount of renewable energy generated and supplied to the grid at present is 5,800 megawatts. The share of renewable energy to the total amount of energy generated became 20 percent in 2022 and 42 percent in 2035.

Egypt is receiving significant sun hours annually, according to a study by the Environment and Climate change Research Institute (ECCRI). In April 2012, the government has started using solar-powered irrigation as an eco-friendly, low-cost system.

Renewable clean energy resources in Egypt

RaSeed Initiative Green Energy in Agriculture: With 96 % of desert land, a high frequency of clear sky days and solar radiations ranging from 2000 kW/h in the north up to 2600 kW/h (m^2/year) in the south, Egypt is one of the most potential countries in the MENA region for solar energy. The introduction of solar powered pumps presents an opportunity to abandon non-sustainable and non-reliable fossil fuel powered generators. Furthermore, the implementation of solar powered irrigation helps overcoming the risk from fluctuations in fuel supply and prices, and instead guarantees stable and reliable on farm energy supply to avoid crop losses that result from insufficient irrigation.

RaSeed'**** initiative aims to promote the use of Photovoltaic (PV) systems in drip irrigation farming in order to support cost-effective and sustainable agriculture. Therefore, the aim is to introduce high-capacity solar operated water pumps of up to a pump size of 100kW - to the Egyptian agricultural sector. Furthermore, soil in the "New reclaimed Lands" is mostly sandy, and water used for irrigation is ground water. Hence, it is crucial to use water efficient irrigation systems. RaSeed targets farm specific optimization of drip irrigation systems that enable maximum fuel savings and water efficiency by taking into account soil compositions and environmental conditions.

In order to further the initiative, a Private Public Partnership (PPP) was established with a solar energy firm (Ashoff Solar) that is supported by the multi-donor initiative 'Powering Agriculture - an Energy Grand Challenge for Development'.

Together with its partners, RaSeed establishes a network, providing high quality solar energy technology and training in Egypt.

Three pilot projects that were initiated mostly at the end of 2014 are supported by the RaSeed initiative in order to promote and assess the feasibility and efficiency of solar energy irrigation systems under different conditions - hot weather, high soil salinity and sandstorms. They are implemented across Egypt, allowing for a pluralistic analysis of solar irrigation systems in desert areas over time. The three pilot projects' locations were SEKEM- the Bahareiya Oasis, WADI FOOD- in Wadi El Natroun and PICO- El Mansoureya. **(Energypedia, 2022)**

RaSeed is composed of the words Ra & Seed. Ra refers to the pharaonic god of the sun, which stands for energy and life, while a seed is the basis for all agricultural activities. At the same time, RaSeed can be translated to 'Credit' in Arabic.

Benban solar park: Egypt has built its largest solar power plant, the Benban solar park in Aswan governorate, it is currently the 4th largest solar power plant in the world.

Benban Solar Park is a photovoltaic power station with a total capacity of 1650 MW nominal power which corresponds to an annual production of approximately 3.8 TWh. It is located in the western desert, approximately 650 km south of Cairo and 40 km northwest of Aswan. **(**CGTN Africa, 2023)

The project was initiated as part of Egyptian government's Sustainable Energy Strategy 2035.

Benban is set to generate the equivalent of 90% of the energy produced by Aswan's High Dam. Already home to the most important electricity production plant in Egypt, Aswan is set to meet and implement Egypt's ambition of having 20% clean energy by 2022, and 37% clean energy by 2035. Benban will cover Egypt's electricity needs and edge it forward to become the region 'sane rgyhub .(LolwaReda,2018)

El Dabaa Nuclear Power Plant: It is the first nuclear power plant planned for Egypt and it is located at El Dabaa, Matrouh Governorate, Egypt, about 320 Kilometers northwest of Cairo. **(**Gamal Essam El-Din, 2017 and World Nuclear News, 2022).The plant has four VVER-1200 reactors of AES-2206 design, which are capable of producing 1.2GW each. The first unit is expected to begin commercial operations in 2026 while commissioning of the remaining three reactors is scheduled for 2028, making Egypt the only country in the region to have a Generation III+ reactor. (Shay, Shaul 2015 and World Nuclear News, 2017)

A renewable energy share of ~26% and a nuclear share of ~13% of installed power are targeted by 2052. This would reduce the fossil fuel component to 58% as compared to the current value of 86%. Such a mix is believed to be most appropriate to meet Egypt's energy demand till 2052.

Bioenergy: Turning sludge into energy

The increasing volume of sewage sludge from wastewater treatment facilities is becoming a prominent concern globally. The disposal of this sludge is particularly challenging and poses severe environmental hazards due to the high content of organic toxic, and heavy metal pollutants among its constituents. (Jumoke Mojisola Oladejo et al., 2018). Sewage sludge is a secondary product of the wastewater treatment. Turning sludge into energy is a way to tackle water resources and waste management simultaneously. Sludge-to-energy systems separate, capture, and utilize the methane gas from sewage sludge for energy, instead of releasing it into the atmosphere. Treating and utilizing wastewater as a valuable resource rather than discarding it as waste can create a new stream from which water, nutrients, and renewable energy can be harnessed. Sewage sludge is a residual and semi-solid substance produced during wastewater treatment. It is a threat to the environment as it is one of the major sources of environmental pollution. However, sewage sludge is rich in organic substance, which makes it a perfect substrate for power generation.

Wastewater is 99 percent pure water and 1 percent wastes primarily in the form of organic matter and nutrients such as phosphorus and nitrogen. (United Nations, 2015). During wastewater treatment, the solid sludge (the organic matter and nutrients) is separated from the combined, liquid wastewater. Converting sludge-to-energy requires high temperature and pressure in a process known as thermal hydrolysis, to maximize the amount of methane that can be produced. (Leah Schleifer and Xiaotian Fu, (2018)

Alexandria Governorate has established a unit to generate electricity from sludge. A station to generate power from sewage sludge is established 2021 with a cost of LE 3 billion ($168.2 million), two similar projects were established in Qalyubia's al-Gabal al-Asfar. The project aims to build a unit to treat sludge through anaerobic digestion (also known as methanization) at the East Alexandria wastewater treatment plant. The project has a number of positive impacts, including reducing the quantity of sludge produced and increasing the magnitude of electricity generation given the biogas produced by the sludge treatment as well as creating market outlets for the sludge produced by selling it as a fertilizer to farmers. (Amr Mohamed Kandil, 2018)

Raising Awareness for Nexus

Engaging the farmers in the dialogue of WEF Nexus and the importance of using the resources of water and energy more efficiently to produce food is very important. This can be done through, conducting capacity building workshops to farmers, inviting them to attend relevant conferences such as Cairo Water Week, awarding the distinguished Farmers and research projects that lead to water and energy saving and maximize food production.

EGYPT'S WORLDWIDE POSITION IN RELATION TO WATER-ENERGY-FOOD NEXUS

The wefnexusindex.org***** shows the indicator of Water-Energy-Food Nexus of Egypt as illustrated in Figure 4. WEF Nexus Index, (2022). The Water-Energy-Food (WEF) Nexus Index is a composite indicator that aggregates 21 globally available indicators. The WEF Nexus Index value for Egypt is 52.3, placing the nation in the 116th position in 2022 vs 109th in 2021 for the 173 countries assessed. Egypt has a value of 36.7 for the Water pillar, 61.2 for the Energy pillar and 58.9 for the Food pillar.

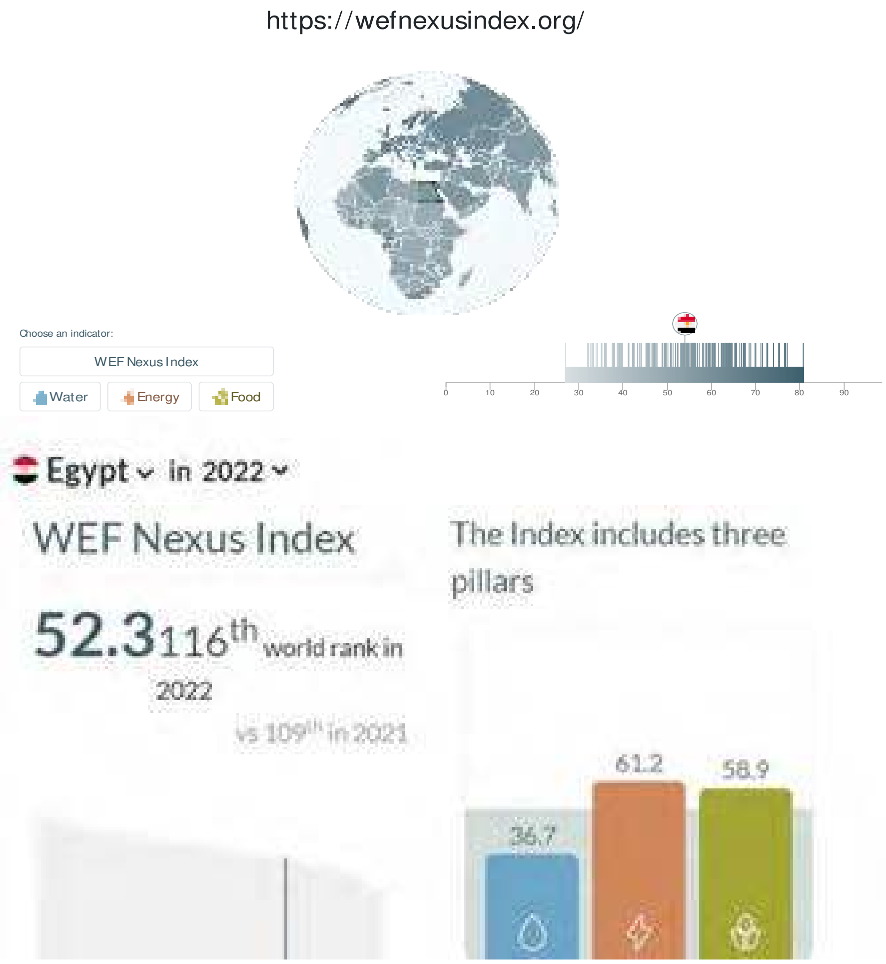

Figure 4. The WEF Nexus Index value for Egypt is 52.3, placing the nation in the 116th position among the countries assessed. [WEF Nexus Index, (2022)]

***** **https://wefnexusindex.org** The WEF Nexus Index. A country-level composite indicator developed using the water-energy-food (WEF) nexus as its guiding framework.

CONCLUSION

This report showed how the relevant state institutions in Egypt faced the problems of water scarcity, food and lack of energy sources by applying modern irrigation systems, lining canals, developing non-conventional water resources, decreasing the areas of water-consuming crops such as rice, sugarcane, as well as expanding the areas of renewable energy in multiple regions across the country, by using modern scientific and technological methods to achieve the goals of Nexus.

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ASSESSMENT OF ON-FARM WATER-ENERGY-FOOD-ECOLOGY NEXUS FOR WHEAT AND FABA BEAN FARMING IN EGYPT

Mohie El Din Omar[1], and Vinay Nangia[2]

ABSTRACT

Egypt has deficiency in water, energy, and yield due to water shortage and the global oil price surge. The current study aimed at developing and applying an on-farm water-energy-food-ecology (WEFE) nexus index for diagnosing farm performance combining the four pillars and considering equal weighting. The index was applied on 2,042 wheat fields and 245 faba bean fields representing different inputs, soil types, fertilizer rates, irrigation systems, and agroecological conditions. The water pillar value was obtained as the ratio of saved water to maximum water consumption perceived in the country on the farm level. The energy pillar value was obtained as the ratio of saved energy to maximum energy consumption perceived. The food pillar value was the ratio of actual yield to maximum yield being 7.49 and 5.7 ton/ha for wheat and faba bean, respectively. The ecology pillar was obtained as the ratio of reduced amount of CO_2 emission to maximum emission. The highest ten indices among 2,042 wheat fields were recorded in newly reclaimed fields of sandy soils and drip irrigation using deep groundwater. Also, 51 out of 52 new reclaimed fields had above average value. The lowest ten indices recorded in old agricultural lands of clay soils and flood irrigation, and only 333 out of 1,780 fields exceeded the above average value with a percentage of 18.7%. The furrow irrigation in 153 out of 184 fields in old agricultural lands exceeded the above average value with a percentage of 83.15%. Likewise, faba bean fields in newly reclaimed lands had the highest rankings, where 61.11% of these fields exceeded the above average value, but only 41% of fields in old agricultural lands exceeded the above average value. The study emphasizes that for both wheat and faba bean farming, the fields in newly reclaimed lands with drip irrigation, had the best performance in the country combining water, energy, food, and ecology pillars.

1. Introduction

The performance of and interconnection between water, energy, food, and ecology sectors have been assessed at the national level for most countries. Simpson et al. (2020) presented a national-level composite indicator that has been established for 181 countries for the assessment of applicable water, energy, and food (WEF) related indicators. The WEF Nexus Index value for Egypt is 52.9, placing the nation in the 121st position among the 181 countries assessed. Egypt has a value of 42.4 for the water pillar, 60.8 for the energy pillar, and 55.4 for the food pillar. In order to strengthen the interlinkage between the foure pillars and the practicaility of the nexus approach, its assessment should be downscaled from the national level to the farm level.

In Egypt, agriculture is consuming 85% of all current available freshwater resources. The agriculture sector currently suffers from land fragmentation, lack of appropriate good agricultural practices, outdated extension systems, low investment, deteriorating water quality, poor water and fertilizer management, poor involvement of the community, and unreliable and inequitable distribution of water along canals. Egypt relies entirely on irrigated agriculture, where water from canals and groundwater. The latter is lifted by pumps as the water level in distribution canals is lower than fields' levels. Future reclamation projects and plans for desalination and wastewater reuse will require additional energy, dependent predominantly on diesel fuel which subsequently increases the carbon dioxide (CO_2) emissions. Land reclamation for agricultural use is one of the top priorities of the agricultural sector in Egypt, in

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which the energy is the main determinant of agricultural sustainability. In recent years, the energy sector has been struggling due to highly increased prices and a shortage of diesel supply. Generating solar energy might expose the water to overconsumption as the solar energy is abundant.

It is clear that interventions to address the security of one WEF element can affect the other elements. Hence, there is a need to have an on-farm WEFE Nexus index presenting a diagnosis for each farm performance combining the four pillars as a quadrilateral nexus rather than assessing each pillar unilaterally. The current paper introduces an on-farm WEFE Nexus Index as a quantitative measure of farm performance in 2,042 fields for wheat and 245 fields for faba bean based on a questionnaire.

2. Methodology

2.1. The WEFE Index

The importance of each sector at farm level has been debatable among different stakeholders, although the interconnection between the WEF elements and their reliance and impact on ecosystems have become obvious. Therefore, the WEFE index in the current paper was computed as the weighted arithmetic average of the four pillars. This way of equal weighting was used to preserve the equal importance of the WEFE nexus elements. Table 1 presents the four pillars, each of which was described in sections from 2.1.1. to 2.1.4.

Table 1. The WEFE Index pillars and indicators

Pillar	Indicator	Pillar Value (%)	WEFE Index (%)
Water	$\frac{Saved\ Water}{Maximum\ Water}$	0 - 100	0 - 100
Energy	$\frac{Saved\ Energy}{Maximum\ Energy}$	0 - 100	
Food	$\frac{Agricultural\ Yield}{Maximum\ Yield}$	0 - 100	
Ecology	$\frac{Saved\ CO2\ Emission}{Maximum\ CO2\ Emission}$	0 - 100	

The calculation of WEFE pillars is based on data collected from a wheat survey of 2,042 fields and a faba bean survey of 245 fields of smallholder farming in Egypt. Data included farm and production practices, soil types, crop rotation and yield, seeds, sowing and fertilizer application, irrigation management, weed, insect and pests, and harvesting. The survey locations represented different agroecological conditions (Figure 1).

Figure 1. Locations of 2,042 wheat fields (left) and 245 faba bean fields (right)

2.1.1. The Water Pillar

At each tested farm, valuation of water pillar depends on the amount of irrigation water saved in comparison to the maximum water consumption experienced in the country. The maximum water consumption was found in old lands where surface flood irrigation without land levelling was applied, in which farmers released the water from one side in the field by gravity until it reached corners at the other side. Due to the land systematic irregularity, much water was applied to reach the field entirely. Among the 2,042 wheat fields of this survey, the maximum amount of applied irrigation water was found with traditional flood irrigation practice as 5,647 m^3/ha. When other irrigation practice was applied reducing this maximum water amount, the resultant saved water amount was computed as the difference between maximim water amount and actual water amount. Then, the ratio of saved water to the maximum water was was obtained. For instance, in another field with a drip irrigation system applied only 1,788 m^3/ha, then the water saving was 3,859 m^3/ha, resulting in an water pillar value of 70%. The water pillar values in 2,402 wheat fields were calculated that way. Likewise, the maximum amount of applied irrigation water in faba bean fields was found with traditional flood irrigation practice to be 4,315 m^3/ha, and the water pillar values in 245 fields were calculated as the ratio of saved water to the maximum water.

2.1.2. Energy pillar

The direct on-farm energy consumption depends on the type of irrigation system, water source, and operational practices. Surface irrigation systems consume less energy than pressurized irrigation systems. Also, pumping of water from a surface canal consumes less energy than pumping from groundwater. Diesel fuel is the main source of energy in agricultural machinery and water pumps in Egypt, and sometimes electrical pumps are used for water withdrawal. The energy equivalent is 56 Megajoules (MJ) for one liter of diesel in average and 3.6 MJ for one kilowatt (KW) of electricity (Yafuz et al., 2014). In the current WEFE index, all energy consumptions either using diesel or electricity were computed in MJ. The indicator value of energy pillar was the ratio between the saved fuel energy amount to the maximum fuel energy consumed. In addition to direct on-farm energy consumption, there is indirect energy consumption due to manufacturing fertilizers and pesticides outside the farm. Figure 2 shows the energy consumption elements and their values. The highest specific energy for water pumping was with sprinkler irrigation from deep groundwater with a value of 3.9 MJ/m^3 (Yafuz et al. 2014), while the lowest specific energy was with flood and furrow from canal water with a value of 0.1 MJ/m^3 (Farag, 2019). The specific energy for field operations for all irrigation systems was 63 MJ/hour (Canakci et al. 2005). Regarding the indirect energy consumption, the specific energy for nitrogen, phosphate, and potassium fertilizers were 66.14, 12.44, and 11 MJ/Kg, respectively (Rafiee et al. 2010). The seeds specific energy was 3.6 MJ/Kg (Beheshti Tabar et al. 2010). The pesticides specific energy was 275 MJ/Kg (Audsley et al. 2009).

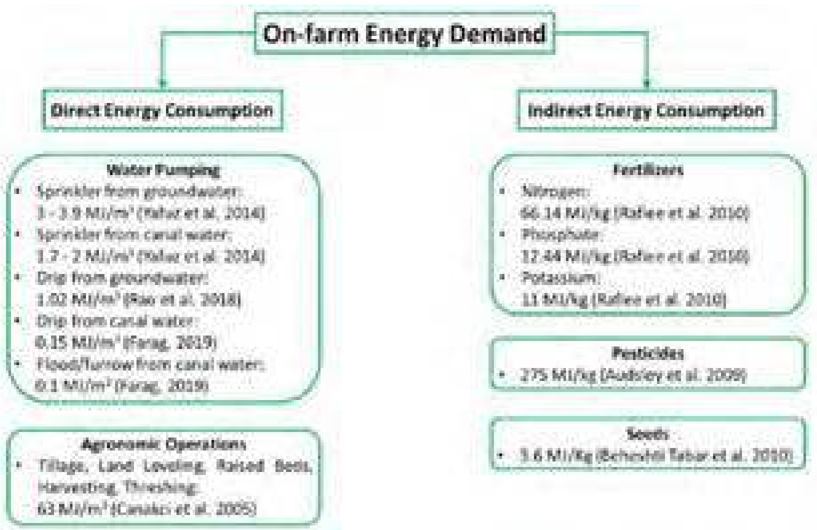

Figure 2. Energy on-farm consumption elements

Although, the sprinkler irrigation from deep ground water has the highest specific energy, the maximum on-farm energy consumption among 2,402 wheat fields was found with the flood irrigation system. The total consumed energy in this field was 91,173 MJ/ha divided into pumping of 5,647 m^3/ha of irrigation water and land operations for a duration of 8 hours, as well as for indirect energy consumption to provide 76 and 100 kg/ha of N and P fertilizers, respectively, to an area of 0.07 ha (1,071 kgN/ha and 1,429 kgP/ha) and of 10 kg of seeds (143 kg/ha). This maximum on-farm energy demand for wheat was computed as follows:

- Energy for water pumping = 5,647 m^3/ha * 0.1 MJ/m^3 = 564.7 MJ/ha
- Energy for operation = 63 MJ/ha/hour * 8 hours = 504 MJ/ha
- Energy for N Fertilizer = 66.14 MJ/kg * 1,071 kg/ha = 70,836 MJ/ha
- Energy for P Fertilizer = 12.44 MJ/kg * 1,429 kg/ha = 17,777 MJ/ha
- Energy for seeds = 3.6 MJ/kg * 143 kg/ha = 514.3 MJ/ha

For other irrigation methods or agronomic practices, this maximum energy consumption is used, the saved energy amount was computed and its ratio to the maximum energy consumption was obtained. For example, the total energy consumption in another field tested in this study was 43,845 MJ/ha divided to 12,064 MJ/ha for water pumping by a sprinkler irrigation system withdrawing the water from groundwater, 126 MJ/ha for two hours of land mechanical operation, 31,120 MJ/ha for fertilizers, and 535 MJ/ha for seeds. The energy saving was 47,382 MJ/ha, and the indicator value of energy pillar in this case was 52%. Likewise, the maximum on-farm energy consumption among 245 faba bean fields with the flood irrigation system was found to be 73,638 MJ/ha, and the indicator values of the energy pillar in all 245 faba bean fields were calculated as the ratio of saved energy to the maximum energy.

2.1.3. Food pillar

The indicator value of the food pillar was the ratio between the actual grain yield from each field to the maximum yield recorded among the 2,402 wheat fields which was 7.49 ton/ha. For example, a field producing 2.88 ton/ha had an indicator value of 38.5% which was a ratio between 2.88 ton/ha to 7.49 ton/ha. Also, the maximum yield recorded among the 245 faba bean fields was 5.7 ton/ha, and the the indicator values of food pillar were calculated as the ratio between actual faba bean yield to the maximum yield recorded among the 245 faba bean fields

2.1.4. Ecology pillar

On-farm CO_2 emission is one of the key elements deteriorating the environment and increasing the heat trapping in the atmosphere. The main source of CO_2 in agriculture is the fuel consumption, mainly the diesel consumption. One liter of consumed diesel in the field produces 56 MJ and 2.5 kg of CO_2 (Guatam et al., 2020).). Also, one KWh of consumed electricity produces 3.6 MJ and 0.82 kg of CO_2 due to the burning of fossil fuels for electricity generation (Schlömer, 2014). The total amount of CO_2 emission from each field of the current survey was estimated based on the total on-farm energy demand and the total amount of consumed diesel. The CO_2 indicator value was calculated as the ratio between the reduced amount of CO_2 emission to the maximum amount of CO_2 emission. The maximum on-farm energy demand for wheat among the 2,402 fields was 91,173 MJ/ha with diesel water pumping, producing 4,070 kg of CO_2 computed as following:

$$\text{Amount of Diesel , in Liters} = \frac{91{,}173\ \text{MJ/ha}}{56\text{MJ/L}} = 1{,}628\ \text{L/ha}$$

$$CO_2\ \text{emission} = 1{,}628*2.5 = 4{,}070\ \text{kg/ha}$$

If the CO_2 emission in another field was 1,764 kg/ha, the CO_2 saving was 2,306 MJ/ha, and the indicator value of the ecology pillar, in this case, was 57%. Likewise, the ratios of saved on-farm CO_2 emissions in all 2,402 fields to the maximum energy consumption were obtained as indicator values of the ecology pillar.

3. Results

The WEFE nexus index was calculated for 2,042 wheat fields and 245 faba bean fields in Egypt representing different inputs, tillage types, seeding rates, sowing and fertilizer applications, irrigation systems, soil types, and agroecological conditions. The values of WEFE nexus index in all 2,042 fields were presented in Figure 3 with an average value of 48.49%, and the highest and lowest values of 87.33% and 18.69%, respectively.

The highest and lowest ten ranking wheat fields for the WEFE nexus index with descriptions of different conditions and practices are shown in Table 2 and Table 3, respectively. The highest ten values were found in newly reclaimed lands in El-Menia governorate, where sandy soil was predominant and drip irrigation from deep groundwater was applied. Among the 2,042 fields investigated in the current study, 52 fields had the drip irrigation system withdrawing the water from deep groundwater, mostly in new reclaimed lands. Out of 52 fields applying drip irrigation, 51 fields had values above the average values. Also, 30 fields had the sprinkler irrigation system, out of which only 12 fields had values above the average value of all 2,042 fields with a percentage of 40%.

In old agricultural lands, where flat land with flood irrigation was predominant and characterized by heavy clay soil, 1,780 fields were tested in this study. Only 333 fields exceeded the above average value of the 2,042 fields with 18.7%. It is worth mentioning here that the lowest ten values were found in flat lands with flood irrigation. Raised bed land with furrow irrigation was also found in old lands, where 184 fields were tested in this study, out of which 153 fields exceeded the above average value with 83.15%.

N fertilization rates in 61% of fields exceeded the generalized recommended value set by the Ministry of Agriculture and Land reclamation (75 N units /feddan or 4,200 m^2), and P fertilization rates in 53% of fields also exceeded the recommended value (15 P_2O_5 units /feddan). This observed overfertilization was not reflected on food pillar values, although it increased the indirect energy consumption and accordingly reduced both the energy and ecology pillar values.

The survey for faba bean was collected from only 245 fields in seven governorates but showed similar findings to the wheat fields. The WEFE nexus indeces are presented in Figure 3 with an average value of 46.82%, and the highest and lowest values of 71.14% and 19.54%, respectively. Only 18 fields represented newly reclaimed lands in Aswan governorate with sandy soil and drip irrigation from deep groundwater, where 11 fields exceeded the above average value of the 245 fields with 61.11%. On the other hand, only 41% of fields in old lands exceeded the above average value with 83.15%.

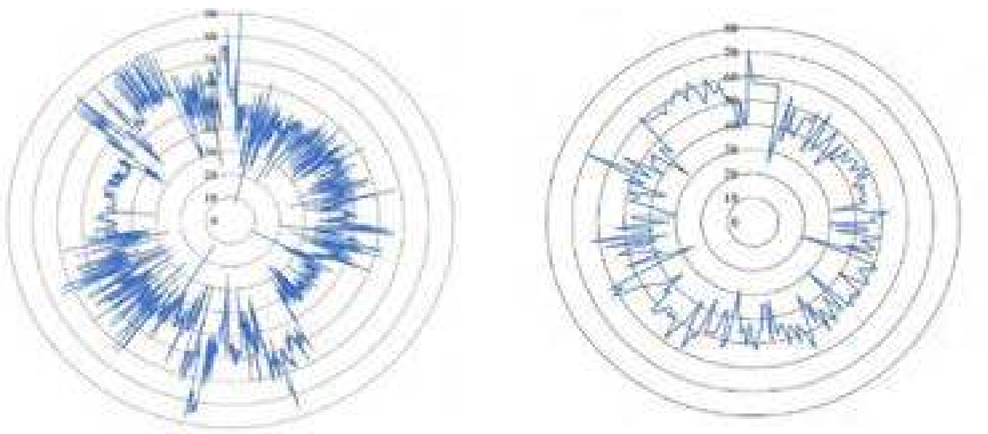

Figure 3. WEFE nexus index values in 2,042 wheat fields (left) and 252 faba bean fields (right)

Table 2. The ten highest ranking wheat fields with description of agronomic practices

Field Description	**WEFE Index (%)**
1.68 ha in Menia governorate with sandy soil, 35 kg seeds/ha on dry soil, tillage, 95 kg Urea/ha, 60 kg of Single Super Phosphate (SSP)/ha, 1,724 m^3/ha by drip irrigation from groundwater with 15 m depth, 100 min machinery for seeding, 60 min machinery for harvesting. (SSP means Single Super Phosphate)	87.34 (Water (W): 70, Energy (EN): 94, Food (F): 90, Ecology (EC): 94)
1.26 ha in Menia governorate with sandy soil, 50 kg seeds/ha on dry soil with tillage, 95 kg Urea/ha, 60 kg NH_4-NO_3/ha, 1,724 m^3/ha by drip irrigation from groundwater with 15 m depth, 100 min machinery for seeding, 60 min machinery for harvesting	86.41 (W: 70, EN: 91.78, F: 92.1, EC: 91.78)
1.6 ha in Menia governorate with sandy soil, 45 kg seeds/ha on dry soil with tillage, 95 kg Urea/ha, 60 kg SSP/ha, 1,724 m^3/ha by drip irrigation from groundwater with 20 m depth, 60 min machinery for seeding	86.37 (W: 70, EN: 91.78, F: 92.1, EC: 91.78)
2.1 ha in Menia governorate with sandy soil, 57 kg seeds/ha on dry soil with tillage, 95 kg Urea/ha, 60 kg NH_4-NO_3/ha, 1,724 m^3/ha by drip irrigation from groundwater with 15 m depth, 100 min machinery for seeding, 60 min machinery for harvesting	85.26 (W: 70, EN: 91.78, F: 92.1, EC: 91.78)
8.4 ha in Menia governorate with sandy soil, 76 kg seeds/ha on dry soil with tillage, 185 kg Urea/ha, 60 kg NH_4-NO_3/ha, 1,724 m^3/ha by drip irrigation from groundwater with 15 m depth, 100 min machinery for seeding, 60 min machinery for harvesting	84.90 (W: 70, EN: 87.8, F: 93.68, EC: 87.8)
1.68 ha in Menia governorate with sandy soil, 74 kg seeds/ha on dry soil with tillage, 190 kg Urea/ha, 1,724 m^3/ha by drip irrigation from groundwater with 15 m depth, 100 min machinery for seeding, 60 min machinery for harvesting	84.57 (W: 70, EN: 88.1, F: 92.1, EC: 88.1)
2.1 ha in Menia governorate with sandy soil, 60 kg seeds/ha on dry soil with tillage, 152 kg Urea/ha, 60 kg NH_4-NO_3/ha, 1,724 m^3/ha by drip irrigation from groundwater with 10 m depth, 100 min machinery for seeding, 60 min machinery for harvesting	84.39 (W: 70, EN: 90.92, F: 85.74, EC: 90.92)
1.6 ha in Menia governorate with sandy soil, 57 kg seeds/ha on dry soil with tillage, 127 kg Urea/ha, 79 kg NH_4-NO_3/ha, 1,724 m^3/ha by drip irrigation from groundwater with 15 m depth, 60 min machinery for seeding, 80 min machinery for harvesting	84.07 (W: 70, EN: 87.1, F: 92.1, EC: 87.1)
2.1 ha in Menia governorate with sandy soil, 57 kg seeds/ha on dry soil, 152 kg Urea/ha, 48 kg NH_4-NO_3/ha, 1,724 m^3/ha by drip irrigation from groundwater of 15 m depth, 20 hr land preparation machinery, 2.5 hr harvesting, 500 min threshing	82.42 (W: 70, EN: 87, F: 85.74, EC: 87)
4.2 ha in Menia governorate with sandy soil, 62 kg seeds/ha on dry soil, tillage, 152 kg Urea/ha, 48 kg SSP/ha, 97 kg NH_4-NO_3/ha, 1,724 m^3/ha by drip irrigation from groundwater of 15 m depth, 100 min machinery for seeding, 240 min harvesting	82.13 (W: 70, EN: 83.2, F: 92.1, EC: 83.2)

Table 3. The ten lowest ranking wheat fields with description of agronomic practices

Field Description	WEFE Index (%)
1.26 ha in Fayoum governorate with clay soil, 143 kg/ha of dry seeds on dry soil, 381 kg Urea/ha, 476 kg SSP/ha, 24 kg NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation from canal water, 690 min machinery for land preparation, and 540 min machinery for threshing	24.40 (W: 0, EN: 39.44, F: 19.05, EC: 39.44)
0.42 ha in El-Nubaria in El Behira governorate with calcareous soil, 171 kg/ha of seeds on irrigated soil before planting, 362 kg Urea/ha, 952 kg SSP/ha, 476 kg NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation from canal water, 90 min machinery for land preparation, 90 min machinery for seeding, and 120 machinery for harvesting	24.20 (W: 0, EN: 0.93, F: 95.27, EC: 0.93)
0.21 ha in Fayoum governorate with clay soil, 143 kg/ha of seeds on dry soil, 381 kg Urea/ha, 619 kg SSP/ha, 238 kg NH_4-NO_3/ha, 5,764 m^3/ha by ha by flood irrigation from canal water, 1,170 min machinery for land preparation, and 1,170 min machinery for threshing	23.82 (W: 0, EN: 23.72, F: 47.63, EC: 23.72)
0.07 ha in Sharkia governorate with clay soil, 143 kg/ha of seeds on irrigated soil before planting, 357 kg Urea/ha, 714 kg SSP/ha, 1,428 kg NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation from canal water, and 60 min machinery for land preparation	23.68 (W: 0, EN: 6, F: 82.92, EC: 6)
1.2 ha in Sharkia governorate with clay soil, 300 kg/ha of seeds on dry soil, 666 kg Urea/ha, 170 kg SSP/ha, 1,400 kg NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation from canal water, 480 min machinery for land preparation, 180 min machinery for seeding, 360 min machinery for harvesting, and 360 min machinery for threshing	23.64 (W: 0, EN: 23.47, F: 47.63, EC: 23.47)
0.10 ha in Menofia governorate with clay soil, 180 kg/ha of seeds on irrigated soil before planting, 400 kg Urea/ha, 500 kg SSP/ha, 500 kg NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation from canal water, and 240 min machinery for land preparation	23.41 (W: 0, EN: 34.12, F: 25.14, EC: 34.12)
1.2 ha in Salhia in Sharkia governorate with sandy soil, 13 kg/ha of seeds on dry soil, 42 kg Urea/ha, 42 kg SSP/ha, 42 kg B-NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation, 60 min machinery for land preparation, 60 min for harvesting, and 60 min for threshing	23.13 (W: 0, EN: 34.2, F: 24.13, EC: 34.2)
0.25 ha in Menofia governorate with clay soil, 48 kg/ha of seeds on dry soil, 100 kg Urea/ha, 200 kg SSP/ha, 400 kg NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation from canal water, 120 min machinery for land preparation, 120 min machinery for seeding, 120 min machinery for harvesting, and 120 min machinery for threshing	21.24 (W: 0, EN: 5.3, F: 74.34, EC: 5.3)
0.42 ha in Sharkia governorate with clay soil, 143 kg/ha of dry seeds on dry soil, 100 kg Urea/ha, 238 kg SSP/ha, 475 kg NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation from canal water, 60 min machinery for land preparation, 60 min machinery for seeding, 60 min machinery for harvesting, and 60 min machinery for threshing	19.54 (W: 0, EN: 0, F: 93, EC: 0)
0.08 ha in Menofia governorate with clay soil, 188 kg/ha of dry seeds on irrigated soil before planting, 438 kg Urea/ha, 625 kg SSP/ha, 1,250 kg NH_4-NO_3/ha, 5,764 m^3/ha by flood irrigation from canal water, and 240 min machinery for land preparation	18.96 (W: 0, EN: 16.73, F: 42.7, EC: 16.73)

4. Discussion

From the results, there are many factors on the farm level determining the WEFE status including the irrigation system, water source, planting method, seeding rate and date, fertilization rate, energy source, machinery for land preparation and yield harvesting and threshing. In general Egypt has a wide range of WEFE Index values obtained from 2,042 wheat fields ranging from 18.69% to 87.33% and in 245 faba bean fields ranging from 71.14% to 19.54%.

The observable low values in fields of flat lands with flood irrigation are attributed to the high-water losses and water consumption as the water is withdrawn from one side in the field and flows by gravity until it reaches the corners of the other side. Also, land irregularities and land depressions collect water that is then lost by evaporation. Therefore, flat lands with flood irrigation have the maximum water consumption in Egypt, and accordingly, the water pillar severely declines. Due to this high-water consumption in flat lands with flood irrigation, their energy consumption exceeds the energy consumption in fields with drip and sprinkler irrigation although their specific energy for water pumping per water volume unit is much less.

Raised bed with furrow irrigation achieves relatively higher WEFE Index than flat lands with flood irrigation in old lands, but in general food pillar values have similar values. Since the ecology pillar is linked to the energy pillar, flat lands with flood irrigation have also low values for ecology pillar in general. The set values of observed food pillar are similar for most of the 2,042 wheat fields and 245 faba bean fields of well drained, free of weeds, and served tillage, regardless the applied irrigation systems.

It can be noticed that the highest ranking wheat and faba bean fields have relatively large areas and are undertaking integrated resources management by applying the drip irrigation system consuming less water and energy and recommended seeds and fertilizers rates as well as by providing well drainage, weed removal, and tillage. The consolidation of fragmented lands where farmers retain ownership of their lands but with cooperative farming is an advantage. This agrees with Giller et al. (2021) who reported that increasing farm sizes in North-West Europe resulted in increased production and a reduction of negative impacts on the environment.

Understanding the land use and changes is important to manage the WEF nexus resources efficiently. This agrees with Wolde et al. (2021) proving that land use and change can resolve the current dilemmas between land, water, energy, and food sector policies, improve resource productivity, lower environmental pressure, and enhance human wellbeing and security. Also, it is noticed that drip irrigation achieves a better status of water, energy, food, and ecology than other irrigation systems. This agrees with Khalifa et al. (2020) and Deshmukh (2015) who have shown that water saving, electricity saving, irrigation efficiencies and yield of crops using drip irrigation are substantially higher than crops irrigated by the conventional flood irrigation methods.

To achieve high on-farm WEFE Index values in Egypt, no specific package can be recommended to the entire country due to the discrepancy in agroecological conditions and soil characteristics. It is recommended to further investigate the potential of drip irrigation in old lands with heavy clay soils. It is also recommended to revisit estimation of the applied irrigation supply to flat lands with flood irrigation, because the high-water consumption in these fields is the main cause of having very low WEFE nexus index.

5. Conclusion

The current paper narratively assesses the status of each WEFE sector individually on the farm level in 2,042 wheat fields and 245 faba bean fields in Egypt.The paper also examines the interrelationships between on-farm WEFE sectors under different agroecological conditions and irrigation and agronomic practices in the country. The high ranking fields are relatively large in new reclaimed lands with sandy soils and an integrated package of resources in which drip irrigation system, recommended seeds and fertilizers rates, well drainage, weed removal, and tillage are applied. The low-ranking fields are in old lands with clay soils, flood irrigation system without land leveling, and overfertilization. It is recommended to further investigate the potential of drip irrigation in old lands with heavy clay soils. It is also recommended to revisit estimation of applied irrigation supply in old lands with flood irrigation, because the high-water consumption in these fields is the main cause of having a very low WEFE nexus index.

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ENHANCING CLIMATE CHANGE RESILIENCE AND ADAPTATION THROUGH INTEGRATED NEXUS APPROACHES

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ABSTRACT

Climate change is a complex challenge, cutting across all socio-economic and ecological sectors. Sectoral adaptation initiatives only exacerbate existing challenges, create system imbalances, and retard sustainable development as those same challenges manifest in other sectors. Therefore, climate change resilience and adaptation initiatives need to be addressed through systemic, integrated, and transformative ways. This study applies the water-energy-food (WEF) nexus integrative analytical model to assess climate change impacts in southern Africa and assess progress towards Sustainable Development Goals (SDGs). The linkages between SDGs and nexus planning facilitated integrated and sustainable management of resources towards climate change resilience and adaptation. Current management of the interlinked WEF resources is presented through a spider web graph that indicates unbalanced resource management, a scenario compounding maladaptation in southern Africa. The assessment guides strategic policy formulations that lead to sustainable resilience and adaptation. As climate change impacts are cross-sectoral and multidimensional, there is an urgent need to adopt and operationalise nexus planning and other transformative approaches to expedite resilience-building initiatives.

Keywords: Sustainability development, resource management, risk reduction, global change, transformational change, resilience building.

1 INTRODUCTION

There are various spheres of activity where nexus concepts have been introduced to increase the understanding of interconnected systems. Although the water-energy-food (WEF) nexus has been the dominant nexus type, other nexuses have emerged over time. In 2014, the United Nations' Sustainable Development Report addressed the aspects of sustainability through nexus concepts such as (i) the climate-land-energy-water nexus; (ii) the oceans-livelihoods nexus; (iii) the industrialization-sustainable-consumption-and-production nexus; and (iv) the infrastructure-inequality-resilience nexus (UN, 2014). Some studies have developed the water-health nexus (Confalonieri and Schuster-Wallace, 2011), the water-milk nexus (Amarasinghe et al., 2012), the water-health-environment-nutrition nexus (Nhamo and Ndlela, 2021), urban nexus (Lehmann, 2018; Nhamo et al., 2021), rural-urban nexus (Constant and Taylor, 2020), and the water-soil-waste nexus (Hülsmann and Ardakanian, 2014). Such an array of nexus types brought about new terms like nexus thinking and nexus planning as a way of moving away from the dominance of the WEF nexus (Naidoo et al., 2021b; Nhamo and Ndlela, 2021).

The increasing focus on the nexus approach implies an interest in interactions, inter-relationships, and inter-connections, such as among sectors or activities, within practical and essential themes for society (Ghodsvali et al., 2019; Naidoo et al., 2021b). These interactions might take the form of interdependencies, constraints, and synergies that arise when changes in one area affect others (Naidoo et al., 2021b; Nhamo et al., 2018a). They might be viewed as either positive or negative in their impacts (Nhamo et al., 2018b). Holistic consideration of such interactions is often referred to as 'nexus thinking or planning' or taking a nexus approach (Venghaus and Hake, 2018). A study conducted in 2015 traced the use and development of

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nexus concepts related to natural resource use through the 1980s and 1990s (Scott et al., 2015). These included pairwise considerations of the bi-directional linkages between water and food, water and energy and energy and food (Hoff, 2011). By 2008, the WEF nexus was the clear focus of several authors, leading to Bonn's influential nexus conference in 2011 (Hoff, 2011). Since then, research interest and activity on nexus planning have accelerated exponentially (Liphadzi et al., 2021), leading to such developments as the Water, Energy, and Food Security Nexus Resource Platform (https://www.water-energy-food.org/) and a Global Nexus Secretariat.

Several attempts have been made to develop WEF nexus analytical tools to examine the WEF resources' diverse interactions as they form the basis of climate change adaptation and resilience building initiatives (Albrecht et al., 2018; FAO, 2014; McGrane et al., 2018; Waughray, 2011). Even so, and besides the various attempts to develop WEF nexus analytical tools, such tools have not been widely adopted as most of them continued pursuing sectoral or linear approaches, or there is no cross-sectoral integration and analysis that promote transformational change (Albrecht et al., 2018; Mabhaudhi et al., 2021; Nhamo et al., 2019). Thus, the main limiting factor with pioneer nexus planning models is the pursuit of sector-based models without a clear integration of the linked sectors (Nhamo et al., 2020a). For the WEF nexus to be an inclusive transformative approach, it has to be a decision support tool that provides holistic assessment and management of interlinked resources, eliminating a "silo" approach (Mabhaudhi et al., 2021).

Although the WEF nexus approach is envisioned to harness the three interlinked global security concerns of access to water, sustainable energy, and food security, some gaps are hindering the approach from being fully operationalised (Naidoo et al., 2021b; Nhamo et al., 2019). Critiques of the WEF nexus point to the volume of theoretical literature that is being published daily since 2015, but only focusing on the importance of the approach without the rigour of empirical evidence (Liu et al., 2017; Nhamo et al., 2018b; Terrapon-Pfaff et al., 2018). Promising attempts have been made, though, in recent years on developing practical and integrative models (Nhamo et al., 2020a).

Holistic management of WEF resources and the elimination of the traditional sector-based linear approaches have the potential to improve existing efforts to enhance resource security, enhance climate change adaptation and resilience and achieve sustainable development (Dargin et al., 2019; Endo et al., 2017). This study uses the analytical model by Nhamo et al. (2020a) to develop a WEF nexus-based methodological framework to guide strategic policy decisions on climate change adaptation and to assess progress made on achieving related SDGs.

2 METHODS

2.1 The Analytic Hierarchy Process (AHP)

Of the various Multiple-criteria decision-making, MCDM methods available in the literature, the AHP remains the most acceptable and widely used because of its robustness as demonstrated by comparative studies on MCDM methods (Tscheikner-Gratl et al., 2017; Velasquez and Hester, 2013). The completeness of the AHP has seen it being applied in various science fields that include Environmental Sustainability, Economic Wellbeing, Sociology, Programming, Resource Allocation, Strategic Planning, and Project/Risk Management to integrate diverse and different indicators to monitor performance, for benchmarking, policy analysis, and decision-making (Cherchye and Kuosmanen, 2004; Dizdaroglu, 2017; Forman and Gass, 2001; Zanella et al., 2013).

The AHP has provided useful results in these fields, and recently, the WEF nexus integrates distinct but interlinked indicators, which generally cannot be analysed through linear approaches.

Despite the subjective decisions that are intrinsic to the AHP, it remains pivotal in policy decisions and performance evaluation as it captures both subjective and objective assessments (Cherchye et al., 2007). The uncertainty that is embedded in the AHP analysis due to subjective considerations is substituted by incorporating reliable baseline data that indicates the real situation on the ground as well as the determination of the consistency ratio (CR) (Brunelli, 2014; Zhou et al., 2007).

2.2 The WEF Nexus integrative model

The WEF nexus indicators were integrated by using the Analytic Hierarchy Process (AHP), which is an MCDM method (Saaty, 1977). The aim was to establish the numerical relationships among the WEF nexus components, simplify their intricate relationships, identify priority areas for intervention, minimise trade-offs and maximise on synergies. The AHP, introduced by Saaty (Saaty, 1987), is a theory of measurement to derive ratio scales from discrete and continuous paired comparisons to help decision-makers set priorities and make the best decisions. The AHP comparison matrix is determined by comparing two indicators at a time using Saaty's scale, which ranges between 1/9 and 9 (Saaty, 1977).

2.3 WEF nexus sustainability indicators

The essence of the WEF nexus is its integrated systems approach and cross-sectoral management of resources and its envisaged role in achieving sustainability in resource use and management (Naidoo et al., 2021b). The emphasis is to ensure that the developments and transformations in one sector should only be executed after considering the impacts on the other sectors (Mpandeli et al., 2018). As sustainability indicators are measurable parameters that evaluate progress towards sustainable development, they are a fitting yardstick to assess progress towards SDGs through the WEF nexus (Nhamo et al., 2020a). The link between SDGs and the WEF nexus is that both address indicators related to resource security that include availability, accessibility, self-sufficiency, and how they influence respective production (productivity) (Bizikova et al., 2013). The resource security indicators (availability, accessibility, self-sufficiency, and productivity) constitute the key drivers in resource management (Flammini et al., 2017). The same indicators also form the basis of socio-ecological and environmental sustainability (Rasul and Sharma, 2016). Within the WEF nexus sustainability indicators, there are pillars that support the indicators. These pillars are essential when determining the quantitative relationships among indicators. Each WEF nexus sustainability indicator and related pillars are considered when determining the numerical linkages of resource management.

3 RESULTS AND DISCUSSION

3.1 Linkages between WEF Nexus and SDGs 2, 6 and 7

Since 2011, the WEF nexus has been promoted as an approach that enhances the cross-sectoral and integrated management of resources, ensuring that any planned developments in one sector should only be implemented after considering the impacts (synergies, trade-offs, and implications) in the other two sectors, as well as its ability to identify different interventional priorities (Mpandeli et al., 2018; Nhamo et al., 2019). Thus, the approach is concerned with resource sustainability and security, which are determined by factors such as availability, accessibility, self-sufficiency, and productivity, from which related indicators are defined, and used to measure resources management and sustainability (Bizikova et al., 2014). Each WEF sector has pillars that sustain respective indicators and contribute significantly when establishing numerical relationships between indicators during the pairwise comparison matrix of the AHP (Nhamo et al., 2020a). Thus, WEF nexus sustainability indicators and pillars (Table 1) are directly linked to related SDGs and are essential for evaluating SDGs implementation progress (Mabhaudhi et al., 2021). Both the WEF nexus and SDGs serve the same purpose of ending poverty and achieving economically and environmentally sustainable outcomes (Naidoo et al., 2021b). The former serves as an approach to spearhead the implementation of WEF nexus-linked SDGs. Table 1 lists WEF nexus indicators and the related SDG indicators.

Table 1. WEF nexus sustainability indicators and the related SDG indicators

Sector	WEF nexus indicator	Related SDG indicator
Water	Proportion of crops/energy produced per unit of water used (productivity)	6.4.1: Change in water-use efficiency over time
	Proportion of available freshwater resources per capita (availability)	6.4.2: Freshwater withdrawal as a proportion of available freshwater resources
Energy	Proportion of population with access to electricity (accessibility)	7.1.1: Proportion of population with access to electricity
	Energy intensity measured in terms of primary energy and GDP (productivity)	7.3.1: Energy intensity measured in terms of primary energy and GDP
Food	Prevalence of moderate or severe food insecurity in the population (self-sufficiency)	2.1.2: Prevalence of moderate or severe food insecurity in the population
	Proportion of sustainable agricultural production per unit area (cereal productivity)	2.4.1: Proportion of agricultural area under productive and sustainable agriculture

Source: Nhamo et al., 2019

The emphasis is on indicators that are directly falling under the WEF nexus framework and speak to the security of water, energy, and food resources, and are framed to improve integrated efficiencies in resource use and management to attain sustainability. These WEF nexus attributes are reflected in SDGs 2, 6, and 7. The capability of the WEF nexus to establish an integrated numerical relationship between interlinked sectors and give an overall synopsis of resource management sustainability over time, simplify the monitoring and assessment of progress in implementing related SDGs indicators (Mabhaudhi et al., 2021).

3.2 WEF nexus framework to assess sustainable development.

This study establishes a framework to guide policy and decision-makers to assess progress towards SDGs and enhances resource security. The framework is based on the WEF nexus analytical model developed by Nhamo et al. (2020a) which focuses on WEF nexus sustainability indicators and establishes the linkages between WEF nexus indicators and related SDGs indicators. This developed framework (Figure 1) provides the required pathways that facilitate an assessment of the progress towards sustainable development over time.

The framework guides strategic policy formulation towards a sustainable future as it establishes an integrated and cross-sectoral numerical relationship among different but interlinked sectors. The framework guides coherent strategic decisions towards sustainability and resource security as it indicates priority areas needing urgent interventions (Nhamo et al., 2020a). The framework provides an overview of the interlinkages among different WEF nexus and SDGs sustainability indicators using the AHP, a multi-criteria decision-making (MCDM). The AHP determines composite indices for each indicator to quantitatively relate the differing WEF sectors. These attributes are critical in integrated and cross-sectoral resource use and management. The WEF nexus tool block (the block to the left in Figure 1) establishes the essence of the tool and what the WEF nexus approach is envisaged to achieve. The success of the WEF nexus as a framework for achieving sustainability is reliant on good governance that underpins the WEF nexus implementation towards socio-ecological sustainability (Bizikova et al., 2013; Hoff, 2011).

The block on integrated analysis and SDGs assessment (second block of Figure 1) establishes the linkages between WEF nexus indicators (Nhamo et al., 2019) and related SDG indicators (https://unstats.un.org/sdgs/metadata/). An assessment of the progress towards achieving sustainability by 2030 (UNGA, 2015) through WEF nexus-related SDGs indicators is achieved by evaluating resource use and management at a given time interval to achieve set SDG targets (Mabhaudhi et al., 2021; Naidoo et al., 2021b). The progress towards a sustainable future is assessed by comparing changes over successive periodic intervals of time (Mabhaudhi et al., 2021). As the WEF nexus identifies priority areas for intervention, it becomes an integrated decision-support tool for implementing sustainability strategies and ensuring economic efficiency and social equity to achieve sustainability by 2030.

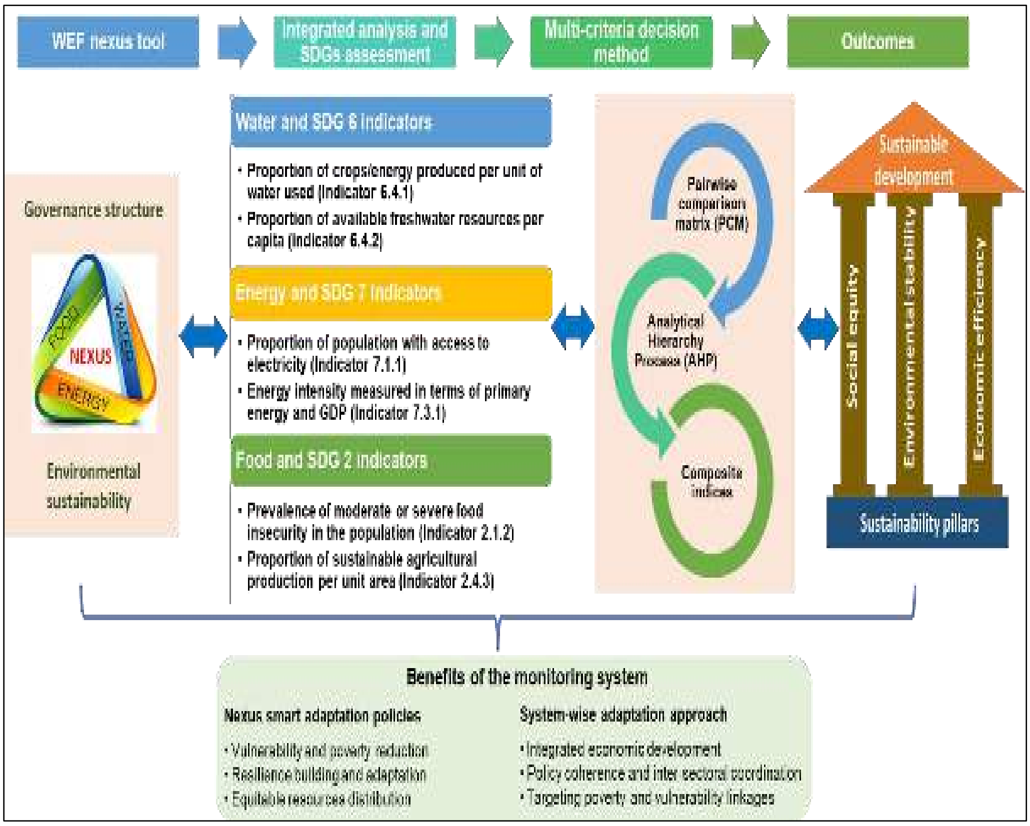

Figure 1. A WEF nexus-based framework to assess progress towards achieving related Sustainable Development Goals

The third block (the MCDM block) represents the model adopted in the framework to quantitatively establish relationships and interlinkages among the WEF sectors at any given spatial-temporal scale (Mabhaudhi et al., 2021; Nhamo et al., 2020a). The fourth block represents the outcomes of the assessment which include social equity, environmental stability, and economic efficiency (Figure 1), the three pillars of sustainable development (UNGA, 2015).

The benefits derived from implementing the SDGs and assessing progress through the systematic and integrated approach of the WEF nexus are given at the bottom of the framework. The success in meeting SDG targets is assessed by the level achieved in promoting prosperity while protecting the planet by not exceeding the planetary boundaries in resource exploitation and use (Kimani-Murage et al., 2021). Good governance is a prerequisite in resource management. It provides political will and reduces vulnerability and poverty, enhancing resilience and adaptation to climate change, equitable resource distribution, integrated economic development, policy coherence, and inter-sectoral coordination.

3.3 Assessing progress towards SDGs over time.

The spider graph indicated in Figure 2 was developed using the AHP, applying the pairwise comparison matrices for 2015 and 2020. The composite indices for the two years were superimposed to assess progress during the five years. The centre pieces are irregular in shape, indicating an unsustainable and siloed management of resources. The development of an integrated WEF nexus analytical framework to achieve sustainability is important for research and policy as it guides the formulations of coherent strategies that drive towards sustainability and resource security (Mabhaudhi et al., 2021). The WEF nexus analytical model (Nhamo et al., 2020a) facilitates an understanding of complex relationships amongst the interlinked sectors and informs a holistic approach to resource management in achieving SDGs. To achieve the SDGs and enhance resource security, and considering their complexity and multidisciplinary nature, the multi-criteria analysis framework provides the decision support tools that facilitate the quantification of the relationships among different but interlinked sectors (Nhamo et al., 2020a). The numerical representation of the interlinked WEF sectors informs strategic policy formulations that lead to sustainability. The level of progress in achieving SDG consists of an evaluation of the progress made towards set goals between different time frames (Figure 2).

The assessment includes measuring the gap between the previous years and the present status. In the example given in Figure 2, the 2020 graph indicates the progress made towards achieving related SDG indicators from 2015. However, the change could either be positive or negative and in the case of negative change, the model indicates areas needing immediate intervention.

The developed framework provides a holistic assessment and intervention by considering all the interlinked sectors in equal terms, including stakeholders, footprints of water production, distribution, and allocation between the linked sectors such as energy costs (Naidoo et al., 2021a). This is critical for long-term and sustainable management decisions as environmental footprints provide insightful indicators that guide informed analysis of WEF resources by

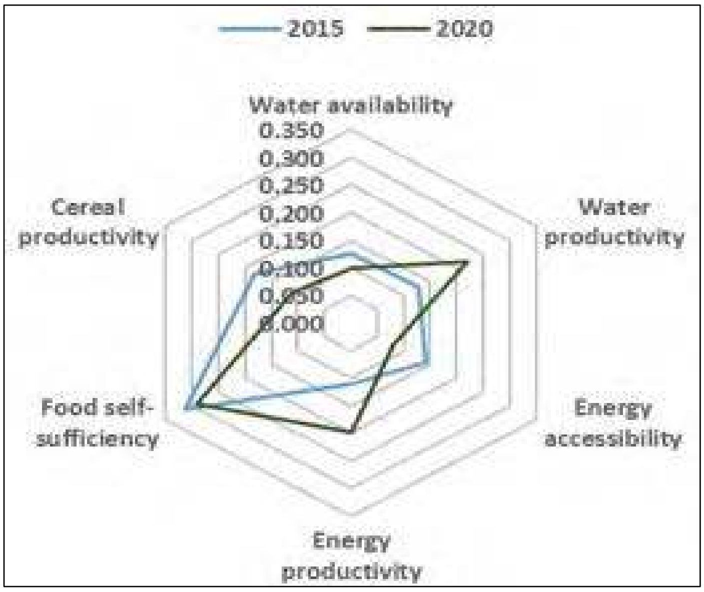

Figure 2. Management of resources over time and the progress towards related SDGs

quantifying synergies and trade-offs along the whole supply chain (Vanham et al., 2019). The identification of these supply chain footprints (diet behaviour, reduction of food losses, and waste) links the WEF nexus with the Circular Economy approach as both are aimed at reducing the effects of consumptive and degradative resources utilisation (Naidoo et al., 2021a). This also enhances the notion that transformative approaches are interlinkages and inform each other (Naidoo et al., 2021b).

The WEF nexus-based analytical framework proposed in this study is capable of identifying and balancing both synergies and trade-offs of an evidence-based nexus practice as it provides an overall overview of the current status of resource management. The framework is developed in such a way that it is applicable at any spatio-temporal scale, depending on data availability (Nhamo et al., 2020b).

4 CONCLUSIONS

The WEF nexus has evolved to become a useful decision support tool to guide integrated solutions in resource management, enhance resilience and adaptive capacities to climate change, and promote strategic resource governance. This study has developed a framework to assist policymakers to address the question of how to achieve integration across the policy cycle and assessing levels of integration at any spatial-temporal scale. The framework guides strategic policy decisions and aids the quantification of WEF sectors' interactions. The framework provides the pathways to identify trade-offs and synergies and provides the lens through which priority areas for intervention are identified. This is critical for monitoring progress towards the SDGs and informing corrective measures needed for effective sustainable development. Apart from being a decision support tool for integrated resources management, the WEF nexus is an important pathway for addressing the challenges of poverty, unemployment, and inequality. The approach promotes integrated planning, decision-making, governance, and management of resources, the needed attributes to achieving simultaneous water, energy, and food security, job and wealth creation, and sustainable natural resources management. The developed framework provides guidelines that enhance cross-sectoral cooperation and mitigate conflicts, increasing resource-use efficiencies in the process. The common attributes between the WEF nexus and SDGS lead to (a) promotion of sustainable and efficient resource use, (b) access to resources for vulnerable population groups, (c) maintenance and support of underlying ecosystem services, and (d) improvement of human wellbeing. Importantly, the WEF nexus approach addresses the five key elements of the SDGs, i.e. People, Planet, Prosperity, Peace, and Partnership, the main factors needed to achieve sustainability.

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STATUS OF IMPLEMENTATION OF THE WATER-ENERGY-FOOD (WEF) NEXUS APPROACH: CASE OF SOUTH AFRICA AND ZIMBABWE

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ABSTRACT

Sectoral approaches to management of Water-Energy-Food, WEF resources ignore the linkages between WEF resources and often exacerbate competition and trade-offs. The web of linkages connecting water, energy and food resources is termed the water-energy-food (WEF) nexus, an approach that recognises the interconnectedness of WEF resources. However, little has been done at sub-national scales to assess the state of implementation of the approach. Therefore, this study sought to (i) assess the status of implementation of the WEF nexus approach, and (ii) make recommendations for its implementation in South Africa and Zimbabwe. The study applied multiple methods including observations, key expert stakeholder input and the web-based and GIS-enabled integrative water-energy-food nexus analytical modelling tool (iWEF, https://www.iwef.app/) in two catchments and two districts in South Africa and Zimbabwe. With a maximum possible value of 1 for the integrated composite WEF nexus index in the iWEF model, the four case studies had marginal sustainable management of between 0.189 and 0.209, indicating a need for more effort to improve resource management. All four case studies depicted irregular shape of the centrepiece in the radar chart which was evidence of unbalanced resource management.

Keywords: nexus, operationalisation, local, SDG, iWEF, resource security, Africa

INTRODUCTION

Water, energy and food are fundamentals for socio-ecological sustainability, human and environmental health, dignity and prosperity (Leal Filho *et al.*, 2018). Together with land, these strategic resources sustain livelihoods and catalyse economic development (DWS, 2018). However, continued depletion and degradation of the three resources amidst climate change threaten humankind's ability to achieve the Sustainable Development Goals (SDGs). Governance and management frameworks have been put in place to guide the management of the three resources in a holistic, systematic and sustainable manner. Despite these ambitious and noble commitments, efforts to meet the set goals have been slow.

The insecurity of WEF resources can be attributed to sectoral planning which has led to trade-offs and insecurity traps. For example, incentives such as rural electrification and subsidies on water, energy and agricultural inputs led to increased water and energy consumption,

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groundwater overexploitation and depletion, and environmental degradation in US Great Plains, Syria, South Asian countries (India, Pakistan, Nepal, Bangladesh), Iran, Mexico, Morocco (Mirzaei *et al.*, 2019). Production of biofuels in sub-Saharan Africa intensified competition between biofuel crops and food crops and ultimately the trade-offs between water, energy and food security (HLPE, 2013; Subramaniam *et al.*, 2020). Thus water, energy and food are interconnected and the planning of water, energy and food systems in silos is not an option if society is to secure adequate water, energy and food for all today and in the future.

Continuing to ignore the competition between water, energy and food is at the detriment of the triple bottom line: profit, people and planet. Satisfying increased demands on water, energy and food with existing practices and management approaches is likely to lead to more intense competition for and degradation and depletion of the natural resource base (FAO, 2018). There is a need to think outside and beyond sectoral boxes and silos for better and sustainable development, utilization and management of resources.

Water, energy and food are inextricably and concomitantly linked in a water-energy-food (WEF) nexus such that actions in one sector influence the others, synergistically (mutually beneficial outcomes) or adversely (trade-offs, conflicts - which may potentially include non-optimal outcomes), at different levels and scales (Hoff, 2011; Beekma *et al.*, 2021).

Since its prominence in 2011, the WEF nexus has gained wide recognition and momentum in research and policy dialogues[10], and by international bodies such as the Food and Agriculture Organization of the United Nations, International Renewable Energy Agency (IRENA), United Nations Economic Commission for Europe (UNECE), Intergovernmental Panel on Climate Change (IPCC), the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security (CFS), and the United Nations (UN).

However, there is very little research on Africa that considers all three nexus sectors (WEF) together (Craig *et al.*, 2022) and some authors blame the lack of suitable analytic tools and supporting evidence. Thus, this study sought to assess the state of the implementation of the WEF nexus approach in southern Africa using a case study approach in South Africa and Zimbabwe.

METHODS

Case studies

This study was carried out in two catchments (Inkomati-Usuthu Water Management Area and Mzingwane Catchment) and two districts (Ehlanzeni District and Umzingwane District) in two countries (South Africa, and Zimbabwe) in the southern Africa region. In South Africa, part of Ehlanzeni District overlaps with Inkomati-Usuthu Water Management Area (Figure 1) and they both have very high imbalanced income distribution with Gini indices of 0.602 and 0.604 (2019), respectively (COGTA, 2020).

The Gini index is a statistical distribution of welfare indicators commonly used to measure inequality among individuals or households within an economy. The Gini index measures the gap between the incomes of a country's richest and poorest people and its value ranges between 0 for perfect equality where everyone has the same income, and 1 (or 100%) for maximum inequality where only one person/household has all the income (Eurostat, 2021; Sulla et al., 2022). Inkomati-Usuthu Water Management Area and Ehlanzeni District cover areas of 36409.58km^2 and 27895.58 m^2, respectively.

In Zimbabwe, Umzingwane District is completely enclosed by Mzingwane Catchment (Figure 1). Umzingwane District is Matabeleland South Province and covers an area of 2797 km^2 and while Mzingwane Catchment covers an area of 63000 km^2, hosts approximately 933023 people and 232929 households' people and straddles on parts of three provinces namely Matabeleland South, Masvingo and Midlands (Mabiza *et al.*, 2007; ZimStat, 2023). Mzingwane Catchment forms the Zimbabwean portion of the Limpopo River Basin and consists of four sub-catchments name Upper Mzingwane, Shashe, Mwenezi and Lower Mzingwane (Mabiza *et al.*, 2007).

[10] Nexus. Nexus Regional Dialogues Programme Phase II. https://www.water-energy-food.org/nexus-regional-dialogues-programme

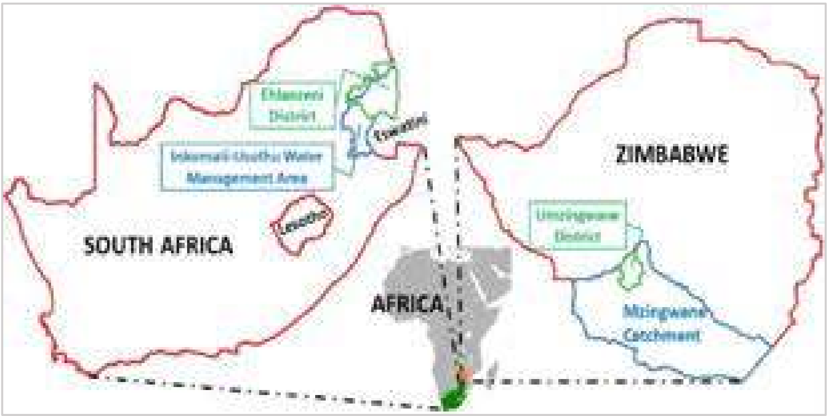

Figure 1: Locations of the four case studies in their respective countries in Africa.

The iWEF 1.0 model

For analysing the WEF nexus in the selected four case study areas, this study applied the web-based and GIS-enabled integrative water-energy-food nexus analytical modelling tool (iWEF) initially developed by Nhamo *et al.* (2020) and further improved and enhanced by Taguta *et al.* (2022). The iWEF support integrated assessment of WEF resources management by using the Analytic Hierarchy Process (AHP) multi-criteria decision-making (Saaty, 1977; Saaty, 1987) to establish quantitative relationships among WEF nexus sustainability indicators and pillars of availability, productivity, accessibility, and sufficiency. The six indicators in iWEF, calculated per annum, are water availability (cubic metres, m^3/capita), water productivity (\$/m^3), energy accessibility (%), energy productivity (gross domestic product, \$GDP / megajoules, MJ), food self-sufficiency (%) and cereal productivity (kilogrammes, kg / hectare, ha). In the current version of iWEF, all the indicators use the same polarity such that higher values are desirable. Water availability is the proportion of available freshwater resources per capita (m^3/capita). Water productivity is the proportion of crops produced per unit of water consumed (\$/m^3). Energy accessibility is the proportion (%) of the total population with access to electricity. Cereal (or crop) productivity is the proportion of sustainable agricultural production per unit area (kg/ha) and it is indicative of the relationship between the area under productivity and sustainable agriculture and the agricultural land area (Nhamo et al., 2020). Energy productivity (EP) measures the economic benefit derived from each unit of energy used (\$GDP/MJ) (ASE and GAEP, 2016). Food self-sufficiency (FSF) is the absence of moderate or severe food insecurity in the population, that is the percentage (%) of individuals in the population who have not experienced food insecurity at moderate or severe levels during the reference year (Nhamo et al., 2020). These six indicators are compared on their relative performance against each other in a pairwise comparison matrix (PCM) by stakeholders (key expert or non-expert or both) based on the hierarchy established through the Saaty analytic hierarchy process and scale (Table 1), and sometimes supported by, if available, expert opinion, literature, or recognized databases (e.g., national statistics, World Bank, Aquastat) (Mabhaudhi *et al.*, 2019; Nhamo *et al.*, 2020).

The Saaty AHP scale ranges from 1 (equal importance) to 9 (the highest and most significant or important relationship) (Saaty, 1977; Saaty, 1987). The pairwise comparison matrix (PCM) or judgement matrix is an output of the pairwise comparison technique wherein experts compare the relative importance or performance of multiple criteria within a defined hierarchical structure of a decision problem (März, 2018). This is typical of the WEF nexus problem wherein there are multiple criteria such as indicators and objectives which require knowledge of their relative performance for informing where, when and how to intervene. The iWEF model uses qualitative data (PCM) based on the Saaty AHP scale (Table 1) from stakeholders in the case study area to quantitatively assess the state of WEF nexus, and quantitative data from established databases and published literature is used to interpret the results from the model. The computation module of iWEF performs three key tasks: (i) determining the consistency of the input pairwise comparison matrix (PCM) of the WEF security indicators, (ii) calculation and normalisation of indices of WEF security indicators by AHP-MCDM technique, and (iii) calculation of the integrated composite WEF nexus index.

Table 1: Saaty's AHP scale of relative performance for pairwise comparisons

Intensity of performance	Definition
1	Equal performance
2	Weak performance
3	Moderate performance of one over another
4	Moderate plus performance
5	Essential or strong performance
6	Strong plus performance
7	Very strong or demonstrated performance
8	Very, very strong performance
9	Extreme or absolute performance
Reciprocals (inverse) of above nonzero	Apply for the opposite of above-mentioned relationships

Note: Odd numbers and their reciprocals are mainly used. Intermediate (even) values and their reciprocals are used when compromise is needed.

Judgements and comparisons for the PCM are subjective in real life, it is difficult for the WEF-related stakeholders to make perfectly consistent judgements especially with multiple criteria (e.g., indicators) and under uncertainty. In most cases, decision-makers tend to make random judgements which lead to a random matrix that is expected to be highly inconsistent. Based on the AHP method, the iWEF model computes the consistency ratio (*CR*), which measures the randomness and consistency of the pairwise judgements from the ratio of the consistency index (*CI*) to the randomness index (*RI*). The *CR* value is calculated as in Mu and Pereyra-Rojas (2017):

$$CR = \frac{CI}{RI} \qquad \text{(Equation 1)}$$

where: *CI* is the consistency index which measures the degree of inconsistency and irrationality of judgements in PCMs, and *RI* is the randomness index which is a measure of how close the judgements of a PCM are closer to a random matrix depending on the order *n* of the matrix or number of WEF security indicators which is six (6) in iWEF model in Table 2 by Saaty and Vargas (2012). If a stakeholder states that "water availability" performs better than "water productivity", and the latter performs better than "energy productivity", their judgements become highly random (high *RI*) and inconsistent (high *CI*) if they mention that "energy productivity" performs better than "water availability".

Table 2: Average random consistency index (*RI*) (Saaty and Vargas, 2012)

n	1	2	3	4	5	6	7	8	9
Random consistency index (RI)	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45

n = six (6) WEF security indicators in the case of iWEF model, thus *RI* = 1.25

CI is calculated as follows:

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad \text{(Equation 2)}$$

where: λ_{max} is the principal or maximum eigen-value estimated by averaging the value of the consistency vector of the PCM, Cv_{ij}, as in Mu and Pereyra-Rojas (2017):

$$\lambda_{max} = \sum_{i=1}^{n} Cv_{ij} \qquad \text{(Equation 3)}$$

where: Cv_{ij} is calculated by multiplying the pairwise comparison matrix (C_{ij}) by the weights vector and then dividing the weighted sum vector by criterion weight (W_{ij}) as in Teknomo (2006), Bunruamkaew (2012), and Mu and Pereyra-Rojas (2017):

$$Cv_{ij} = \frac{1}{W_{ij}} \sum_{ij}^{n} C_{ij} W_{ij} \quad \text{(Equation 4)}$$

Based on the obtained *CR* value, the iWEF model then either accepts if $CR < 0.1$ (or 10%) or rejects it if $CR \geq 0.1$ (Saaty and Vargas, 2012).

If the PCM is consistent, i.e., $CR < 0.1$, the iWEF model proceeds to normalise the provided PCM from which it calculates the normalised indices for each indicator and the overall integrated composite WEF nexus index. The iWEF model computes the normalised indices for the six indicators by taking the eigenvector corresponding to the largest eigenvalue of the matrix and then normalising the sum of the components (Nhamo *et al.*, 2020). The overall importance of each indicator is then determined. The PCM of *n* criteria (in this case, 6 indicators of WEF security), is determined using Saaty's scaling ratios in the order (n X n) (in this case 6 X 6) (Saaty, 1990). As adopted from Saaty and Vargas (2012), *A* is a matrix with elements a_{ji}, which is the decision maker's preference of the i^{th} criterion (e.g., water availability) over the j^{th} criterion (e.g., water productivity). The matrix's reciprocity is expressed as:

$$PCM = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad \text{(Equation 5)}$$

where: $a_{ij} > 0$; $a_{ij} = \frac{1}{a_{ji}}$

After generating this PCM of WEF security indicators, it is then normalized as a matrix *B* with elements b_{ji}, constructed by dividing each element of the PCM by its column sum and expressed as in Saaty and Vargas (2012):

$$B = \begin{bmatrix} \frac{a_{11}}{\sum_{n=1}^{n} a_{n1}} & \frac{a_{12}}{\sum_{n=1}^{n} a_{n2}} & \cdots & \frac{a_{1n}}{\sum_{t=1}^{n} a_{tn}} \\ \frac{a_{21}}{\sum_{n=1}^{n} a_{n1}} & \frac{a_{22}}{\sum_{n=1}^{n} a_{n2}} & \cdots & \frac{a_{2n}}{\sum_{t=1}^{n} a_{tn}} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{a_{n1}}{\sum_{n=1}^{n} a_{n1}} & \cdots & \cdots & \frac{a_{nn}}{\sum_{t=1}^{n} a_{tn}} \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix} \quad \text{(Equation 6)}$$

Each weight value, i.e., normalised index w_i in matrix of normalised indices *W* is computed by averaging across the rows of *B* as in Saaty and Vargas (2012):

$$W = \frac{1}{n} \begin{bmatrix} \sum_{n=1}^{n} b_{1n} \\ \sum_{n=1}^{n} b_{2n} \\ \cdots \\ \sum_{t=1}^{n} b_{nt} \end{bmatrix} = \begin{bmatrix} w_1 \\ w_2 \\ \cdots \\ w_n \end{bmatrix} \quad \text{(Equation 7)}$$

where: $\sum_{i=1}^{n} w_i = 1$

The iWEF model determines the integrated WEF nexus composite index as a weighted average of the normalised indices w_i. The value of the integrated WEF nexus composite index ranges from zero (0, low) to one (1, high) as in Table 3 (Nhamo et al., 2020).

The iWEF model requires delineation of the case study boundaries which can be done manually in the "Map Playground" or automatically by uploading pre-existing shape files in .geojson format. Key outputs from the iWEF model include the (i) *CR* value indicative of the consistency of the stakeholder judgements in PCMs, (ii) integrated composite WEF nexus index indicative of the overall WEF nexus performance of the case study, (iii) spider diagram or radar chart or sustainability polygon plotted from the normalised indices which indicate the relative performance of each indicator and sector, and (iv) map which shows the geographic location and WEF nexus performance of the case study.

Table 3: Performance categories for WEF nexus indicators and the iWEF-derived integrated composite WEF nexus index (Nhamo et al., 2020)

Indicator	Unsustainable	Marginally sustainable	Moderately sustainable	Highly sustainable
Water availability (m^3/per capita)	< 1 700	1 700 ≤ *x* ≤ 6 000	6 000 < *x* ≤ 15 000	> 15 000
Water productivity (US$/$m^3$)	< 10	10 ≤ *x* ≤ 20	20 < *x* ≤ 100	> 100
Energy accessibility (% of pop)	< 20	20 ≤ *x* ≤ 50	50 < *x* < 90	90 ≤ *x* ≤ 100
Energy productivity (USD/MJ)	< 0.11	0.11 ≤ *x* < 0.2	0.2 ≤ *x* ≤ 0.33	> 0.33
Food self-sufficiency (% of pop)	< 70	70 ≤ *x* ≤ 85	85 < *x* ≤ 95	> 95
Crop productivity (kg/ha)	< 500	500 < *x* ≤ 2 000	2 000 < *x* ≤ 4 000	> 4 000
Integrated composite WEF nexus index	0 ≤ *x* < 0.1	0.1 ≤ *x* < 0.25	0.25 ≤ *x* < 0.65	0. 65 ≤ *x* ≤ 1

All indicators share one common indicated scale in the radar chart. The farther away from the centre an indicator is plotted in the radar chart, the higher and desirable its relative performance. The level of sustainability or performance of the integrated composite WEF nexus index together with the quantitative values of the six indicators are all interpreted according to Table 3.

Data collection and analysis

During data collection, key expert stakeholders from WEF-related sectors were asked, from their perception and knowledge of the case study, to qualitatively pairwise compare the performance of the six indicators using the Saaty's AHP scale in Table 1. A simplified version of the data collection tool for PCMs for the iWEF model is shown in Table 4.

Table 4: Pairwise comparison matrix. A simplified version of the data collection tool for collecting iWEF PCMs data from stakeholders.

Indicator pair	Better performing indicator	Rank / weight	Justification
Water availability vs. Water productivity			
Water availability vs. Energy accessibility			
Water availability vs. Energy productivity			
Water availability vs. Food self-sufficiency			
Water availability vs. Cereal productivity			
Water productivity vs. Energy accessibility			
Water productivity vs. Energy productivity			
Water productivity vs. Food self-sufficiency			
Water productivity vs. Cereal productivity			
Energy accessibility vs. Energy productivity			
Energy accessibility vs. Food self-sufficiency			
Energy accessibility vs. Cereal productivity			
Energy productivity vs. Food self-sufficiency			
Energy productivity vs. Cereal productivity			
Food self-sufficiency vs. Cereal productivity			

The judgements from the stakeholders formed the PCMs that were run in the iWEF model to show, from an integrated perspective, the (i) overall WEF nexus performance of the case study as indicated by the integrated composite WEF nexus index, (ii) the relative performance of each indicator and sector as indicated by the normalised indices.

Where and when the PCMs from stakeholders show inconsistency in the iWEF model, the PCMs were run in the AHP Priority Calculator (AHP Online System - AHP-OS) (Goepel, 2018 and 2022) which identifies specific outlier judgements which can be revisited by stakeholders. Established databases and published literature such as from statistical agencies and government reports were consulted for the quantitative values of the six indicators which were used to support interpretation of the results from iWEF modelling. Shapefiles for delineating the case study boundaries were obtained from established sources such as the Municipal Demarcation Board and the Spatial Data Download Tool (Department of Water and Sanitation) of South Africa.

RESULTS AND DISCUSSION

Quantitative values of WEF security indicators

Quantitative values of the six indicators of security of WEF sectors obtained from established databases and published literature indicate that the two case studies are not performing well in terms of the selected WEF security indicators, considering their categories/levels of sustainability provided in Mabhaudhi et al. (2019) and Nhamo et al. (2020) (Table 5).

Table 5: Overview of the WEF nexus indicators for selected case studies in South Africa (2016/2017) and Zimbabwe for the period 2021/2022.

WEF nexus pillar	Indicator and units	South Africa (2016/2017)		Zimbabwe (2012/2022)	
		IUWMA	EDM	MC	UD
1. Water	Water availability (m^3 / cap / yr)	886.8	882.8	<1700	<1700
	Water productivity ($/$m^3$)	4.11	4.90	3.00	2.00
2. Energy	Energy accessibility (%)	87.2	92.7	45.8	48.2
	Energy productivity (GDP/MJ)	0.12	0.17	< 0.11	< 0.11
3. Food	Food self-sufficiency (%)	83.9	85.6	68	73
	Crop productivity (kg/ha)	5418.4	4675.8	302.5	833.3

IUWMA = Inkomati-Usuthu Water Management Area; EDM = Ehlanzeni District Municipality; MC = Mzingwane Catchment; UD = Umzingwane District. (Sources: Eskom; Food and Nutrition Council – FNC; Statistics South Africa – StatsSA; Zimbabwe National Statistics Agency – ZimStat; Zimbabwe Power Company – ZPC; Zimbabwe Vulnerability Assessment Committee - ZimVAC).

WEF nexus of Inkomati-Usuthu Water Management Area and Ehlanzeni District Municipality in South Africa

The initial PCMs from stakeholders were inconsistent and outside the acceptable ranges for Inkomati-Usuthu Water Management Area (14.1%) and Ehlanzeni District Municipality (37.6%). The same stakeholders were re-engaged to systematically revise some of their judgements and this resulted acceptable ranges of CR values for Inkomati-Usuthu Water Management Area (8.3%) and Ehlanzeni District Municipality (3.9). With integrated composite WEF nexus indices of 0.209 and 0.210 (from a maximum of 1; Figure 2) from the iWEF model run using pairwise comparison matrix (PCM) of the performance of six indicators in IUWMA and Ehlanzeni District, respectively, it is evident that the management of WEF resources in the two case studies in South Africa is marginally sustainable, with a wide gap that needs improvement.

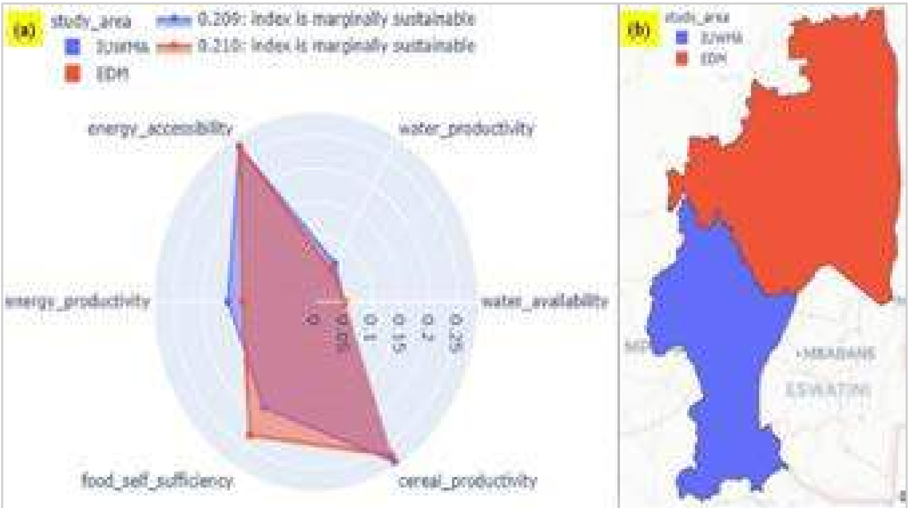

Figure 2: (a) Quantitative, graphical, and (b) spatial representation of the WEF nexus in Inkomati-Usuthu Water Management Area (IUWMA) and Ehlanzeni District Municipality (EDM) in South Africa (colour codes in the map are for distinction and identification; all normalised indices of the six indicators use the same scale in the radar charts/spider diagram).

The irregular shape of the amoeba (centrepiece) is evidence of unbalanced and biased management of the WEF resources (Figure 2). For example in IUWMA, the energy and food sectors (pillars) and their indicators are performing relatively well compared to the water sector (pillar) and its indicators. Cereal productivity and energy accessibility are doing better than all other indicators, followed by food self-sufficiency and energy productivity, and lastly water availability and water productivity.

In Ehlanzeni District, the food sector (pillar and its indicators) outperforms the energy sector (pillar and its indicators) followed by the water sector (pillar and its indicators). Cereal productivity, food self-sufficiency and energy accessibility are doing well compared to other indicators, followed by energy productivity, while water availability and water productivity are performing relatively poorly. These trends in performance could be attributed to different challenges and resource management practices that are prevalent in Inkomati-Usuthu Water Management Area and Ehlanzeni District, as reported by WEF-related key expert stakeholders in the catchment and from literature.

The low performance in water availability in IUWMA and Ehlanzeni District is attributed to scarcity driven by population growth and climate conditions. South Africa's population continues to grow at an average rate of 1.2% per annum, with a huge influx of migrants, thus exerting pressure on demand for the available water resources (Mpandeli *et al.*, 2020; DWS, 2021; StatsSA, 2022).

The low performances in energy indicators are due to some households still using non-modern sources of energy for cooking, lighting and heating. For example, about 82.8%, 88.8%, 83.8% and 63.3% of households in Mpumalanga Province use electricity for cooking, lighting, water heating and space heating respectively, while the rest use gas, solar and unclean sources of energy such as paraffin, fuel generators, firewood, coal, animal dung, and candles (StatsSA, 2016). About 83.7%, 95.3%, 83.8% and 66.3% of households in Ehlanzeni District use electricity for cooking, lighting, water heating and space heating respectively, while the rest use gas, solar and unclean sources of energy such as paraffin, fuel generators, firewood, coal, animal dung, and candles (StatsSA, 2016). The reliability of electricity supply is low due to frequent and intense loadshedding which undermines energy productivity.

Good performances in cereal productivity and food self-sufficiency can be attributed to a relatively good number of households (18.2%) involved in agricultural activities including the production of crops (grain, food) and livestock, poultry, fruits and vegetables for household food and generating some household income (StatsSA, 2016). Similarly, there was good production of the staple maize crop with total yields in 2017 of 2 456 543 tons at approximately 5.81 ton / ha (StatsSA, 2020). Another contributing factor could be the reprioritisation of agriculture by the

South African government in 2010/2011 for food security and poverty alleviation (du Toit *et al.*, 2011; StatsSA, 2016).

WEF nexus of Mzingwane Catchment and Umzingwane District in Zimbabwe

The initial PCMs from stakeholders were inconsistent and outside the acceptable ranges for Mzingwane Catchment (15.6%) and Umzingwane District (28.1%). The same stakeholders were re-engaged to systematically revise some of their judgements and this resulted acceptable ranges of CR values for Mzingwane Catchment (8.6%) and Umzingwane District (2.3%). With integrated composite WEF nexus indices of 0.189 and 0.194 (from a maximum of 1; Figure 3) from the iWEF model run using pairwise comparison matrix (PCM) of the performance of six indicators, the management of WEF resources in Mzingwane Catchment and Umzingwane District is marginally sustainable, with a wide gap that needs improvement.

The irregular shape of the amoeba (centrepiece) is evidence of unbalanced and biased management of the WEF resources (Figure 3). For example, in Mzingwane Catchment, the energy sector (pillar and its indicators) outperforms the food sector (pillar and its indicators) followed by the water sector (pillar and its indicators). Food self-sufficiency and energy accessibility are doing well compared to other indicators, followed by energy productivity, cereal productivity, water availability and water productivity. In Umzingwane District, the energy sector (pillar and its indicators) outperforms the food sector (pillar and its indicators) followed by the water sector (pillar and its indicators). Food self-sufficiency and energy accessibility are doing well compared to other indicators, followed by energy productivity, cereal productivity, water availability and water productivity. Several challenges to WEF security were reported by key expert stakeholders, in literature and noted by observation in the case study areas.

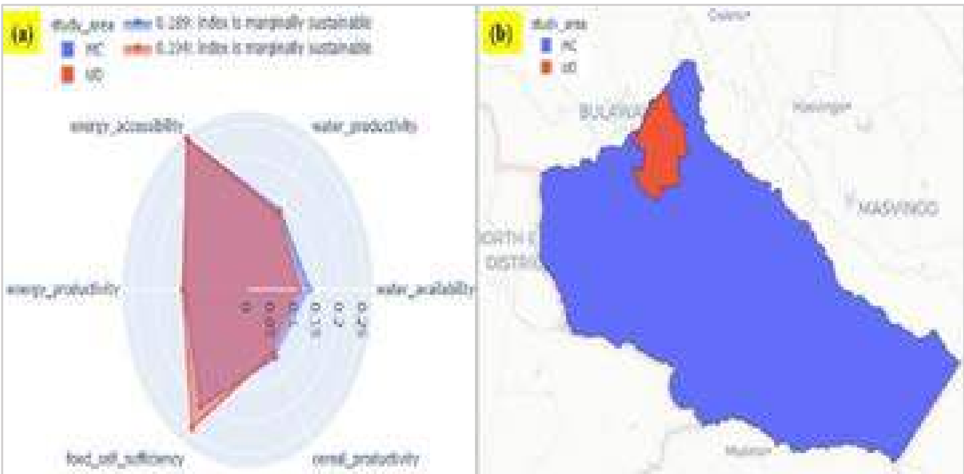

Figure 3: (a) Quantitative, graphical, and (b) spatial representation of the WEF nexus in Mzingwane Catchment (MC) and Umzingwane District (UD) in Zimbabwe *(colour codes in the map are for distinction and identification; all normalised indices of the six indicators use the same scale in the radar charts/spider diagram)*.

The relatively high performance in food security can be attributed to (i) establishments of small-scale irrigation schemes in drier regions for the period 2013 to 2018 which increased areas under irrigation, (ii) stable cereal prices, (iii) the introduction of input support scheme through the special maize and wheat programme (known as “command agriculture”), (iv) increase in the area under climate proofed technologies and initiatives (Pfumvudza / Intwasa) and (v) relaxation of import bans and duties (Muhoyi and Mbonigaba, 2022; ZimVAC and FNC, 2022). However, staple maize production was still suboptimal due to poor rainfalls and dry spells (ZimVAC and FNC, 2022; AU, 2023). Food security is undermined by the operational status of irrigation schemes. In Umzingwane District and by number, 12.5% and 37.5% of irrigation schemes are partially or not functional, respectively. (GoZ, 2022).

Nexus-cautious and - conscious upscaling of promising practices in southern Africa

The "hotspot" sector in all four case studies was water (Table 5, Figures 2 and 3), maybe because South Africa and Zimbabwe are arid, water-scarce and stressed, thus requiring prioritization in interventions and investments while simultaneously balancing the management of WEF resources. Evidence on the ground and in literature shows that there are some operational, ongoing and planned projects and interventions that are being pursued in South Africa and Zimbabwe to improve the security of WEF resources, mainly through augmenting supply and improving resource use efficiency (Table 6).

Table 6: Summary of ongoing operational and planned practices and initiatives, their target sector, and potential synergies (benefits) and trade-offs (risks) on other WEF-related sectors in South Africa and Zimbabwe

TS	Initiative	Nexus dimensions		
		W	E	F/A
Water	Groundwater use	+Water availability	-Energy availability	+Food production
	Rainwater harvesting and storage	+Water availability		+Food production
	Removal of invasive alien vegetation (), e.g., lantana (Lantana camara) (IUCN, 2021)	+Water conservation		
	Improving water use efficiency	+Water conservation	+Energy conservation	
	Wastewater reuse	+Water supply and conservation	+Energy productivity	+Food production
	Rehabilitating (repair, maintenance) and expanding wastewater treatment works	+Water quality	-Energy availability	
	Rehabilitating (repair, maintenance) and expanding water treatment and supply	+Water supply	-Energy availability	
	Expanding water infrastructure	+Water supply	-Energy availability	+Food production
	Retrofitting cooling systems and decommissioning power stations	+Water conservation	+Energy availability	
	Water reallocation and inter-catchment transfers	+Water supply	+Energy availability	+Food production
Energy	Decommissioning of coal-fired power stations	+Water availability	-Energy availability	
	Hydrogen energy	-Water availability	+Energy availability	+Competition for water
	Renewable energy	+Water availability	+Energy availability	+Competition for land
	Battery energy storage systems (BESS)		+Energy management	
	Diesel-based peaking generators and modular reciprocating gas engines		+Energy availability	
	Improving energy efficiency		+Energy conservation	
	Ethanol production	-Water availability	+Energy availability	+Competition for land
Food	Irrigation expansionrehabilitation	-Water availability	-Energy availability	+Food production
	Irrigation rehabilitation	+Water efficiency		+Food production
	Irrigation modernization	+Water conservation	-Energy availability	+Food production
	Grain milling		+Energy availability	+Food production
	Land reform	±Water availability	±Energy availability	±Food production
	Solar-powered drip irrigation	-Water availability;	+Energy availability	+Food production

TS	Initiative	Nexus dimensions		
		W	E	F/A
		+Water conservation		
	Farmer support (mechanization, inputs)		+Energy availability	+Food production
	Climate smart agriculture (conservation agriculture)	+Water conservation		+Food production
	Community nutrition centres and food relief aid			+Food distribution
	Agro-forestry	+Water conservation		+Food production
	Mine land rehabilitation and utilization			+Food production
	Soil and water conservation	+Water conservation		+Food production
	Livestock production (small, large)	-Water availability	+Feedstock	+Food production

TS = target sector; **W** = water; **E** = energy; **F/A** = food/agriculture; **+** : potential synergy or increase; **±** : potentially positive (synergy) or negative (trade-off); **blank** : potentially neutral; **-** : potential trade-off or decrease. Invasive alien vegetation are plants that are introduced into places outside of their natural range, negatively impacting native biodiversity, ecosystem services or human wellbeing (IUCN, 2021). *(Sources: Key expert stakeholders and authors' synthesis from literature)*.

However, these efforts tend to be sectoral planned and implemented but their effects are cross-sectoral (Table 6). Thus, all interventions need to be interrogated from a nexus perspective to minimise cross-sectoral trade-offs that may exacerbate WEF insecurity and leverage on potential synergies across the WEF nexus. Where possible, integrated solutions or decoupling and de-risking of WEF systems must be pursued. There is need for reflection of ambitions by South Africa for green hydrogen production and by Zimbabwe for irrigation expansion, respectively, because both endeavours will strain the scarce water resources. Similarly, large scale renewable and biofuel projects require large areas of lands which may compromise availability of agricultural land and ultimately food security. Low hanging fruits for improving WEF security include rehabilitating partially- and non-functional infrastructure such as irrigation schemes, dams, water treatment and wastewater treatment plants, power plants and boreholes. This will potentially improve their reliability and efficiency. For remote rural areas, opportunity lies in decentralised WEF solutions such as improved rainfed agriculture, hybrid solar-biogas-irrigation system (Winklmaier *et al.*, 2020), solar powered irrigation schemes (Burney *et al.*, 2010; IRENA and FAO, 2021), and waste-to-energy (septic tank-UASB system, BiogasDEWATS) (Adhikari and Lohani, 2019).

CONCLUSION AND RECOMMENDATIONS

Application of the iWEF model in South Africa and Zimbabwe indicated that the management of WEF resources from an integrative perspective is marginally sustainable in all four case studies. The overall WEF nexus performance is low, and the management of WEF resources is unbalanced. This state of WEF insecurity is evident from the ongoing loadshedding, water rationing and hunger issues prevalent in the two countries and characteristic of other countries in southern Africa. There is need for interventions that simultaneously (i) improve the centrality of WEF resources management, and (ii) improve the performance of WEF systems. Current practices and planned and ongoing interventions have potential synergies, and trade-offs that may create a vicious cycle of WEF insecurity. To improve the overall WEF nexus performance while balancing and harmonising the management of WEF resources, need exists to interrogate practices and interventions from a nexus perspective, probably coupled with scenario planning, to inform on systems de-risking and decoupling, and integrated solutions in implementing the WEF nexus approach. Thus, the iWEF model creates an opportunity for identifying and minimizing trade-offs, and harmonisation of activities among the WEF sectors. Furthermore, the tool provides pathways to develop nexus interventions and simultaneously improve the sub-optimally performing sectors.

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TRANSITIONAL PATHWAYS TOWARDS SUSTAINABLE FOOD SYSTEMS THROUGH NEXUS PLANNING

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ABSTRACT

Today's grand challenges that include climate change, resource depletion and degradation, migration, and the emergence of novel pests and diseases, among others, are somehow linked to food systems. The broad interlinkages among these challenges require transformational planning that brings change, enhances adaptation, and reduces the risk to human and environmental health. This study applied nexus planning, a transformative approach, to establish the interconnectedness of food systems and developed a framework to guide strategic policy formulations that enhance resource use efficiency and reduce waste in the environment, and ultimately achieve the circular economy. This can be achieved through sustainability indicators to provide quantitative transitional pathways that lead to the circular economy in the food value chain. An outline of the available options is given to enhance sustainable food systems, highlighting priority areas for intervention and balancing socio-ecological interactions. The premise is to achieve sustainable food systems by analysing food system components in an integrated manner. Achieving socio-ecological sustainability reduces the risk posed by global environmental change and ensures continued provision of ecosystem services. Sustainable food systems are a catalyst for achieving socio-ecological balance and their success hinges on circular modelling and transformative planning.

Keywords: Climate change, Circular economy, Adaptation, Sustainability, Global change, Risk reduction.

1. INTRODUCTION

Agriculture in southern Africa contributes about 20.2% to the gross domestic product (GDP), playing an important role in economic development (Nhamo et al., 2019). However, the region has already lost over 25% of soil fertility over the years due to degradation and overexploitation, further exacerbating the vulnerability of the region (FAO, 2020; Nkonya et al., 2016). This is happening at a time when the sector is expected to produce more food to feed a growing population projected to reach 2 billion people by 2050 in southern Africa (Hall et al., 2017). The growing gap between the demand and supply of food resources requires transformational change in food systems through the adoption of smart and clean production systems that lead to sustainability. Transformative approaches like the water-energy-food (WEF) nexus are anticipated to propel resource security and a cleaner environment (Hall et al., 2017). This is the reason why food systems are at the heart of Sustainable Development Goals (SDGs) and are linked to at least 12 of the 17 goals (Chaudhary et al., 2018; UNGA, 2015).

A sustainable food system refers to an agricultural system that delivers healthy food to meet current food requirements, while at the same time preserving healthy and sustainable ecosystems that are capable of providing food for generations to come, with a controlled negative impact on the environment (Allen and Prosperi, 2016; UNGA, 2015). It is a system that encourages local production and knowledge, providing nutritious and healthy food, which is available, accessible, and affordable to all at all times, and at the same time protecting farmers and workers, consumers, and communities (Eakin et al., 2017). Therefore, transitioning towards sustainable food systems should be built around integrated strategic policies formulated around the intricately linked resources of water, land, environment, and

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energy, as well as nutrition and health (Nhamo and Ndlela, 2021; Wittman et al., 2017). Transitional pathways concern a demarcated trajectory that leads from one situation to another through a particular territory. Transitions are evolutionary and open-ended, they are non-linear, and are based on searching, learning, and experimentation (Geels et al., 2016). They are mainly supported by transformative and circular models which are important in addressing today's challenges that cut across all sectors and, therefore, require integrated, iterative and cross-sectoral interventions (Naidoo et al., 2021). The pathways inform coherent and strategic policies that lead to sustainable adaptation and resilience. This study develops a nexus planning tool and provides the transitional pathways towards sustainable food systems, establishing the interlinkages between food system components.

2. METHODS

2.1 Conceptual framework

As the concept of sustainable food systems is quite complex and cross-sectoral, having various components, a conceptual framework was developed to guide the identification of pathways that drive towards sustainable food systems. The framework is based on the intricately interlinked but distinct components of a food system that include producing, processing, packaging, distribution, retailing, and consuming and how each of the connected systems and components is impacted by climate change and other drivers of change. This is critical to understanding the socio-economic, and environmental interactions and how they are influencing global environmental change.

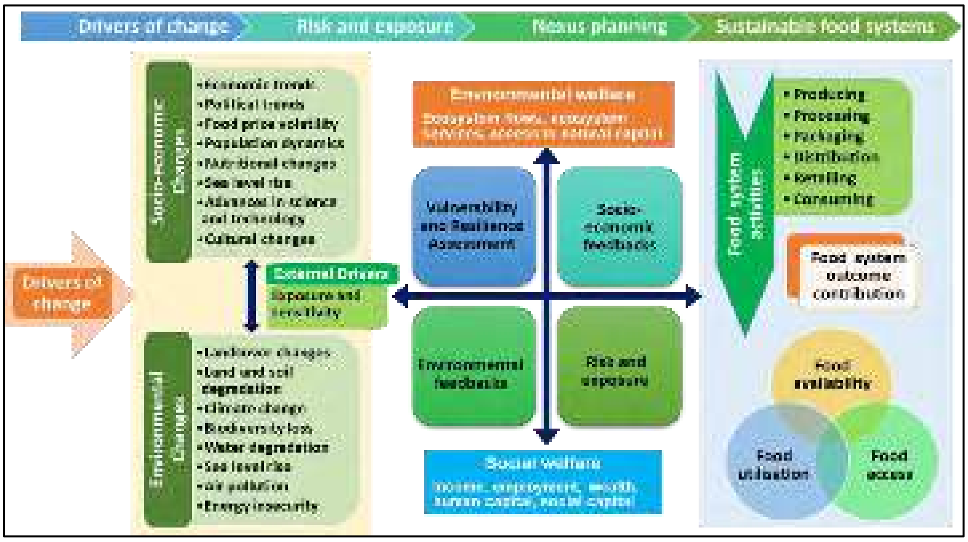

Figure 1. A nexus planning based conceptual framework illustrating the connected processes and interactions needed to achieve sustainable food system.

The derived knowledge facilitated evaluating societal outcomes such as food security, ecosystem services, and social welfare, that result from these interactions (Ericksen, 2008; Tendall et al., 2015). Figure 1 presents the developed framework, illustrating the interlinked processes of a food system, and highlighting the role of nexus planning in transitioning towards sustainable food systems. Nexus modelling is a preferred approach as it facilitates transformational change through its polycentric and circular modelling capabilities (Figure 1).

As food systems are complex social-ecological systems that include various interactions between humans (economic and political trends, food price volatility, population dynamics, changes in diets and nutrition, and advances in science and technology), and natural (land cover changes, land and soil degradation, climate change, biodiversity loss, sea-level rise, and air pollution) components (Béné et al., 2019b; Ericksen, 2008; Marshall, 2015), it is paramount to understand these relationships and assess them holistically. This is the initial phase in transitioning towards sustainable food systems. In between the social-ecological systems are external drivers (Figure 1), which include exposure and sensitivity, that also determine the impact of change on human and environmental health. Knowledge of these drivers and how they influence activities and outcomes of food systems is important for informing policy decisions (Béné et al., 2019a). Food and nutritional security, as well as sound human and environmental health, are the main outcomes of any food system (Nemecek et al., 2016). Thus, a food system is considered vulnerable or resilient depending on its capability to deliver and ensure food security (Ericksen, 2008). According to Figure 1, nexus planning connects these interactions by defining, measuring, and modelling progress towards sustainability, through a set of indicators formulated around resource utilisation, accessibility, and availability (Nhamo et al., 2020). These developments facilitate modelling, monitoring, and simulating some aspects of sustainability.

2.2 Nexus planning as a pathway to attain sustainable food systems.

As nexus planning emphasises providing integrated solutions to distinct, but interlinked components, it is envisaged to provide integrated solutions to the intricately connected food system components (Freeman et al., 2015; Mercure et al., 2019; Nhamo et al., 2020; Nhamo and Ndlela, 2021). Its transformative and polycentric nature allows for an integrated assessment of food system components of production, processing, packaging, distribution, retailing, and consumption, allowing for integrated graphical visualisation of their relationships (Nhamo et al., 2020). This is facilitated by establishing numerical relationships of food system components through sustainability indicators. Sustainability indicators are essential for providing quantitative relationships between distinct components for informed resource management, and sustainable development. The sustainability indicators for food systems are related to food and nutritional security, and human and environmental health (Nhamo and Ndlela, 2021), and include pillars such as availability, accessibility, and utilisation, as well as continued provision of ecosystem services and the reduction of risk of pests and diseases (Fig. 2) (Nhamo et al., 2020; Pérez-Escamilla and Segall-Corrêa, 2008).

Therefore, by considering the heterogeneity of the distinct components of food systems over space and time and their repletion with non-linear societal and environmental feedbacks, nexus planning unpacks and addresses the complex and multi-causal challenges within a food system (Bieber et al., 2018). A set of sustainability indicators related to food systems components are given in Table 1. The indicators are critical for providing a form of measurement that is necessary to assess, monitor and evaluate performance, measure achievement, and determine the accountability of the system (Warhurst, 2002). These are the main elements that are critical in monitoring and evaluation. Therefore, sustainability indicators are basic decision-support tools for transforming complex relationships into simple formulations for easy interpretation, monitoring, and evaluation.

Table 1. Sustainability indicators for assessing the sustainability of food systems.

Food system component	Indicator	Units	SDG indicator
Producing	Proportion of agricultural area under productive and sustainable agriculture	%	2.4.1
	Proportion of land that is degraded over total land area	%	15.3.1
Processing	CO_2 emission per unit of value added		9.4.1
	Manufacturing value added as a proportion of GDP and per capita	%	9.2.1
Packaging	Proportion of medium and high-tech industry value added in total value added	%	9.b.1
	Installed renewable energy-generating capacity	Watts/capita	12.a.1
Distribution	Proportion of the rural population who live within 2 km of an all-season road	%	9.1.1
	Passenger and freight volumes, by mode of transport		9.1.2
Retailing	Number of companies publishing sustainability reports		12.6.1
	Material footprint, material footprint per capita, and material footprint per GDP	Tons/capita	12.2.1
Consuming	(a) Food loss index and (b) food waste index		12.3.1
	National recycling rate, tons of material recycled	Kg or %	12.5.1

In the case of food systems, nexus planning balances competing needs against an awareness of environmental, social, and economic limitations faced by humankind (Nhamo and Ndlela, 2021). It is a transformative way to provide pathways that lead to resilience and adaptation, and at the same time ensure human and environmental health. Therefore, sustainability indicators are an integral part of nexus planning as they form the basic unit of measurement to understand complex interactions (Nhamo et al., 2020). The food systems nexus indicators (Table 1) are linked to related SDGs indicators, making nexus planning a relevant approach for assessing progress towards sustainable development over time. The indicators are used to develop indices that provide insights into the efficiency of processes within a food system (Chaudhary et al., 2018). The essence of establishing the numerical relationships of the components of a system is to indicate priority areas needing immediate intervention and to reduce risk and vulnerability.

3. RESULTS AND DISCUSSION

Pathways towards achieving sustainability of food systems.

As already alluded to, food systems are complex, and interlinked and also significantly contribute to the unsustainability of socio-ecological and economic processes. Thus, building sustainable food systems has become a topical agenda at global conferences, particularly their role in achieving SDGs. The interconnectedness and the systemic nature of the interactions of food systems call for transformative and circular models that lead to integrated assessment to identify the intrinsic properties requiring timely interventions and guide progress towards sustainability. Therefore, it is critical to provide a practical and action-based framework that guides policy and science towards food systems transformations.

A comprehensive food systems framework that guides the transformational change should acknowledge that the sustainability of food systems entails long-term food and

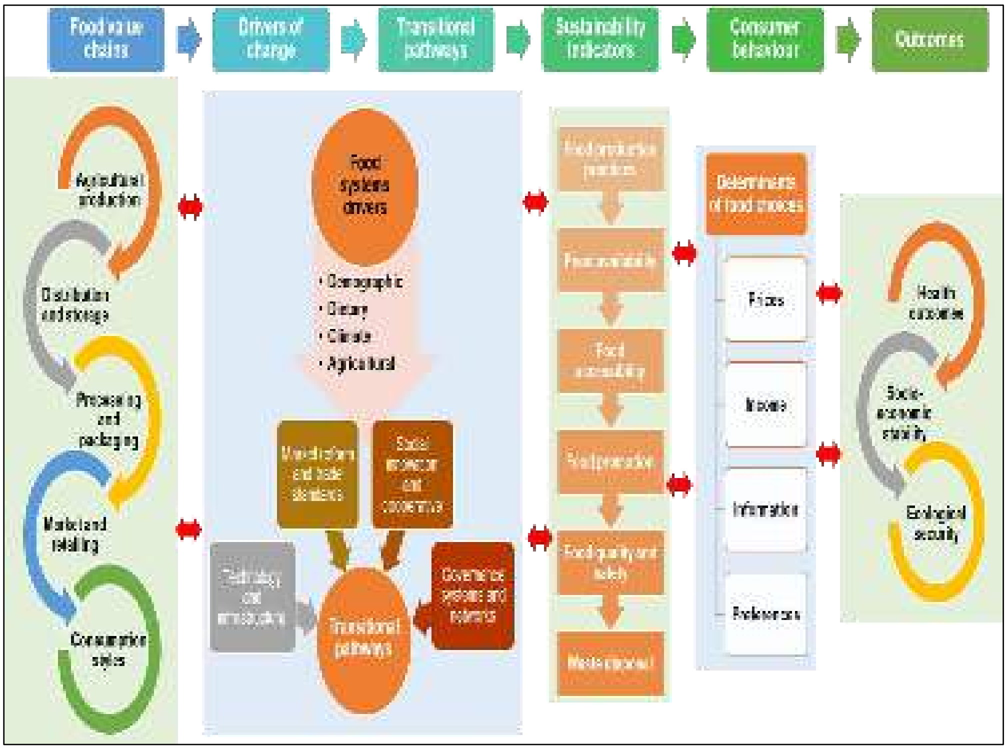

Figure *2*. Transitional pathways towards sustainable food systems, representing an integrated and cross-sectoral interventions towards sustainability

nutrition security in terms of availability, accessibility, utilisation, and stability dimensions (Figure 2) (Nhamo et al., 2020). The acknowledgment is based on meeting the food and nutrition security for the present and future generations, food systems components need to be resilient, efficient, and sustainable (Béné et al., 2019a). The broad intricate interlinkages between food sustainability and food and nutrition security manifest at the global, national, local, and household levels (Mabhaudhi et al., 2016). Therefore, a multi-disciplinary approach that involves multi-stakeholders is needed to achieve sustainable food systems. It is never a one-way or linear approach, but a systemic and circular approach that is iterative.

The transitions, therefore, should include increasing efficiency (sustainable intensification), demand restraint (sustainable diets), and food systems transformations (alternative food systems. The transitional process towards sustainable food systems is a change from an agricultural-centred system to a food system policy and research framework. The stages are critical for integrating complex and holistic transformations in sustainable food systems, which is also a precondition to achieving sustainable food and nutrition security.

The Food Systems Approach (Van Berkum et al., 2018) is being widely used to guide strategic policy formulations towards sustainable food systems and in supporting SDG 2 initiatives on achieving zero hunger. The approach attracts investment and supports innovations that promote healthier diets, and that humankind does not exceed the planetary boundaries. Therefore, the food systems framework (Figure 2) outlines the pathways that provide insights into the structure, behaviour, and performance of the interlinkages between food systems components. The framework differentiates the interrelationships, interlinkages, and feedbacks between three fundamental components that include (Figure 2) (a) food system drivers (urbanization, technology development, climate change, and economic growth), (b) food system components (production, distribution, packaging, retailing and consumption), and (c) food system outcomes (health, sustainability, resilience, and equity).

An important aspect of the framework (Figure 2) is that it identifies potential trade-offs between different dimensions of food systems (access, availability, safety, affordability, and resilience) and how they can be addressed, and how synergies can be enhanced. The framework consists of three major phases that include (Béné, 2020; Brouwer et al., 2020; Fanzo et al., 2021; HLPE, 2017):

a. Societal demands emanating from diverse transitions in agriculture, demography, climate change, and changing diets.

b. Interventional strategies range from novel technologies and market transformations to social innovations and adaptive governance structures.

c. Interventions and leverage points with clear evidence showing the impact on key stakeholders.

Interactions between the three phases provide an overview of the local opportunities and constraints related to distinct interventions and the synergies and trade-offs between the food system components as informed by stakeholder engagement (Brouwer et al., 2020; HLPE, 2017).

4. RECOMMENDATIONS

Transitioning towards a sustainable food system is a complicated process that requires improvements in land use and agricultural practices. Transformational and integrated approaches provide the pathways to sustainable food systems, but to achieve optimum results, we recommend the following guidelines:

a. Integrated pathways should emphasise critical biophysical and economic 'leverage points' in food systems, with a focus on resource use efficiency and on enhancing food production processes and the performance of the environment with the least effort and cost. This calls for the adoption of modern technologies that enhance productivity in all of its domains.

b. Advances that are earmarked to improve agricultural productivity should also consider enhancing the resilience of the food system. Although high-efficiency and mechanised agriculture have many benefits, it is also highly vulnerable to disasters that include extreme weather events, novel pests and diseases, and economic shocks (Calicioglu et al., 2019).

c. There is an urgent need to develop methods to evaluate trade-offs of agricultural practices and balance them with advances in technological developments. Research should develop decision support tools to support management decisions, productivity, and environmental stewardship.

d. Sustainable development in the agriculture sector should be at par with technological development, as informed by circular and transformative modelling which enhance transformational change, ensuring food security and environmental performance of food systems. Current linear models are generally sector-based and only exacerbate existing challenges by focusing on a single sector (Nhamo and Ndlela, 2021).

e. Transitioning towards sustainable food systems is supported by coherent policies that create a strategic and conducive environment for agro-ecology. This is supported by a policy framework that is based on a holistic performance monitoring system that considers nutritional, and environmental impacts and the long-term stability of the system.

Agriculture is the key driver of environmental and climatic change, and as a result, the sector requires a shift from the current linear approaches to circular modelling to enhance food production sustainably. The transformation should be accompanied by societal awareness to catalyse a change from current practices.

5. CONCLUSIONS

The systemic cross-sectoral nature and the intricate interdependencies and interactions of food systems require transformative approaches that address challenges in an integrated manner and simplify human understanding of complex socio-ecological connections. Nexus planning has been used to assess the sustainability of the food system by identifying key properties that support life and healthy environments. The approach has guided policy and supported decision-making to identify priority areas that need immediate intervention, a key step in ensuring food and nutrition security and at the same time protecting the environment. The essence of nexus planning is the capability to examine the multi-causality of dynamic processes within a complex system, including food systems. Indicating priority areas needing immediate intervention paves the way to use scenarios to evaluate various possibilities that lead to coherent strategies. This is critical to understand and appreciate change over time in food security and social and environmental outcomes. These outcomes are dependent on the decisions and actions taken in the activities practiced during the food system but are also impacted by global socio-economic, political, and environmental drivers. Simplifying human understanding of the complex interactions among food system components provides pathways that reduce risk and exposure, an initial step towards sustainable development. This paper has provided these pathways using nexus planning as today's challenges are complex, cut across sectors, and interlinked. Sectoral interventions that do not consider the interlinkages and connectedness of sectors will only compound existing challenges.

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UNDERSTANDING WATER FOOD ENERGY (WFE) NEXUS AND THE CHALLENGES OF IMPROVING MODEL ACCURACY

John O'Connor[1] , Carl Waters[2] and Liz Hutton[1]

ABSTRACT

The ICID WFE Nexus working group is tasked with improving the overall understanding the WFE Nexus and particularly its implications to irrigation and food production. During the 2022 conference in Adelaide a WFE Nexus model was presented for several irrigation regions in India. This model combined sub models of the 3 elements of the WFE Nexus, to identify areas most impacted by the WFE Nexus issues (https://icid-ciid.org/icid_data_web/Workshop_WFEN2022.pdf). However, the nexus elements are not static, so more refinement may be warranted to improve the usefulness and accuracy of such models. As situations vary over time some temporal consideration is likely to improve practical applications of such models, but refinement of water management may also be important.

Keywords: Water Food Energy Nexus Model dynamics

1. INTRODUCTION

The WFE Nexus has been modelled in many ways and Vinca et al. (2021) provide an insight into many of these and how they operate and often link with climate models. A significant comment in this review was the lack of water management related variations.

"What is ignored by all the models is any possible influence of changes in water management, such as creation of new storage reservoirs, river diversion, or increased irrigation on local and global climate." (Vinca et al. 2021).

Integrating water management variables may seem simple, and may be if extractions do not change markedly; but if water extraction locations and crop type irrigated are not static, models will struggle to have practical relevance. Australian examples are used to show fluid nature of nexus elements - which may or may not be relevant in other countries.

In Australia, the development of water markets post 2000 allowed trading of water entitlements and allocations along many river basins, either as a temporary or a permanent trade. This allows water, in drier times, to be used where it is most valued. Generally, this tends to be permanent plantings of fruit or nut trees and vines. This movement of available water means where water is used and for what crop is not static over time and can be a response to dry periods or variation in water availability.

2. RESULTS AND DISCUSSION

In drier years water availability is limited and the trading price increases in line with scarcity (see Fig 1).

In dry years cotton, rice irrigated cropping or even dairy may sell water to permanent plantings, which typically use pressurised delivery systems (needing energy). While in average or wetter years where water is available and its trading price is cheaper, cotton, rice and irrigated cropping industries tend to make use of the larger water volumes available (Fig. 2). With most of this water supplied by gravity systems.

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So, in any year, water availability and irrigation use will change, energy use will change and crop production will change. Additionally crop losses are not always linked to a lack of water or energy; as seen in 2022 where excess rain destroyed crops in irrigation areas due to flooding and prolonged waterlogging, which may add another aspect to consider.

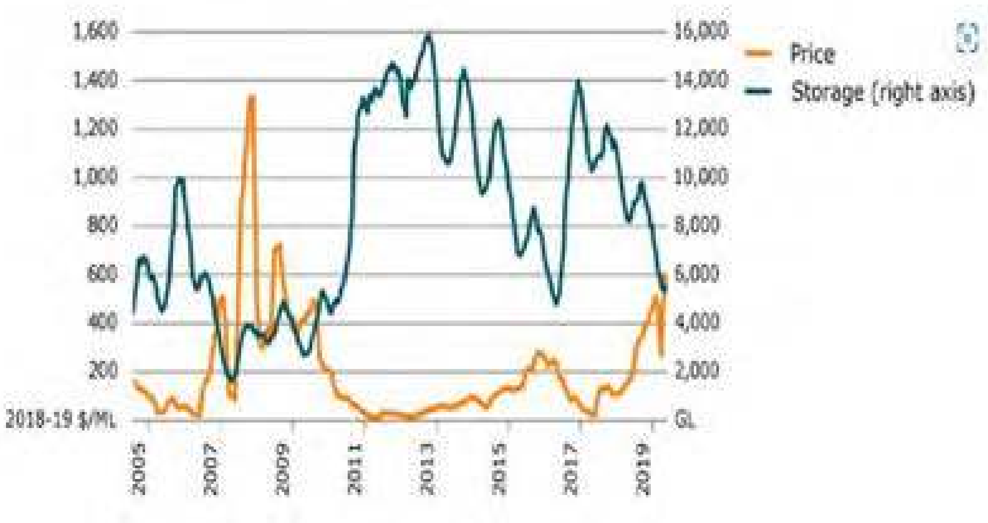

Figure 1. Monthly allocation prices (in ML Australian $) and storage volumes (Mega Litres), southern Murray–Darling basin, MDB between July 2005 to May 2019. Source: Murray-Darling Basin water markets: trends and drivers 2002-03 to 2018-19 - DAFF (agriculture.gov.au)

Introducing further complexity to any Nexus model will challenge modellers but will ensure such models can be of greater value. Further rain/water availability in a series of typical years and the resulting implications may be needed to fully understand the dynamics of the nexus in different locations/ river systems across years. Perhaps a 3 level (Dry Median and Wet year) sub assessment (or similar) is warranted to improve model accuracy across years and understand fluctuations in the W&F components of the WFE Nexus.

The Energy component of the WFE Nexus also can be variable in locations and across years. When water is available gravity systems dominate but in very dry times pressurised controlled delivery systems will be much more prominent and will require power to function. Local availability and economics will dictate the specific technology used but perhaps the CO2 emissions related to the power used may be the measure of most significance in WFE Nexus modelling and useful in relating irrigation to climate change matters. However, this again creates a challenge to modellers to refine models to enhance their value in the real world. As every power generation technology has potentially a different CO_2 loading per KWh/GWh (Figure 3) and every country has a different mix of power generation. An example of country variations in CO2 emissions per KWh as is seen in Figure 4.

3. CONCLUSION

The WFE Nexus is a difficult concept to accurately model due to the highly variable nature of all its components. This is particularly noticeable for water management related factors such as water availability as it changes with rainfall and demand seasonally; crop economics and water movements/ trades along basins and irrigation system. Given these intricacies, one can understand why Vinca et al. (2021) found it was missing from the Nexus models they reviewed. Yet without refinement to a local level, models may not be able to provide the guidance they potentially could to decision makers to test new or developing technology. Introducing further complexity to the WFE

Nexus model will greatly challenge modellers but will ensure such models can be of greater value and use in the real world.

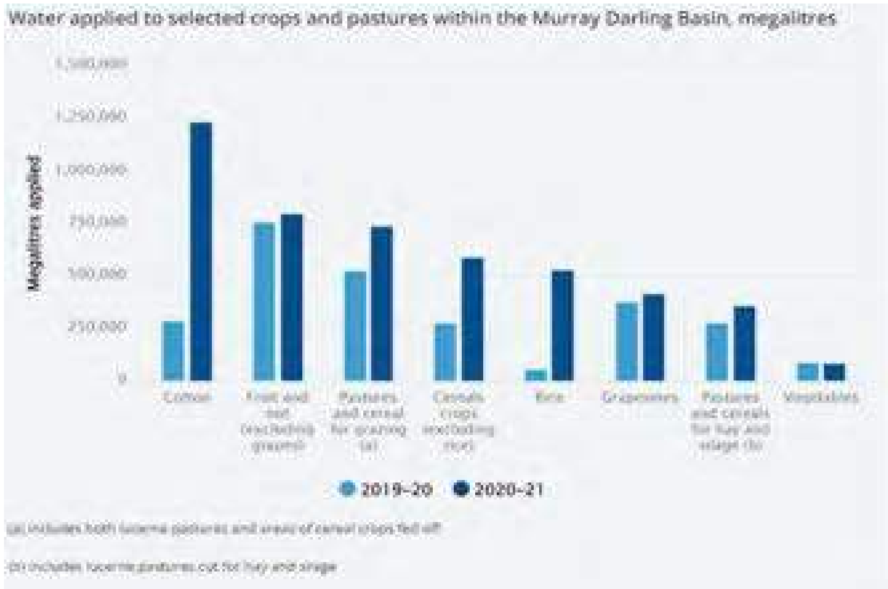

Figure 2. Water applied to selected crops and pastures within the Murray Darling Basin Mega litres) in 2019-20 and 2020-21. Source: Water Use on Australian Farms, 2020-21 financial year | Australian Bureau of Statistics (abs.gov.au) https://www.abs.gov.au/statistics/industry/agriculture/water-use-australian-farms/2020-21

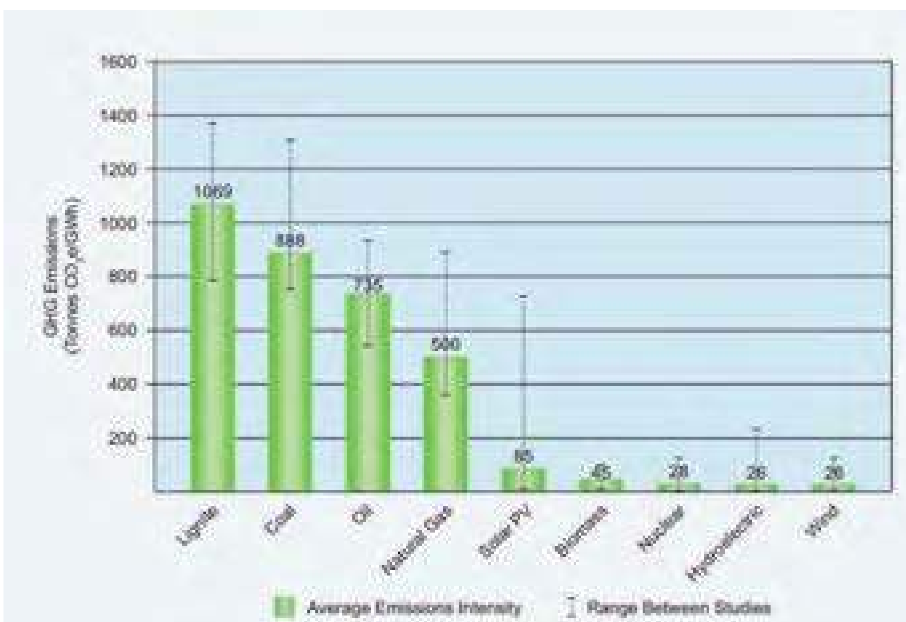

Figure 3. Lifecycle Green House Gases, GHG Emissions Intensity of Electricity Generation Methods. Source: comparison_of_lifecycle.pdf (world-nuclear.org), https://www.world-nuclear.org/uploadedFiles/org/WNA/Publications/Working_Group_Reports/comparison_of_lifecycle.pdf

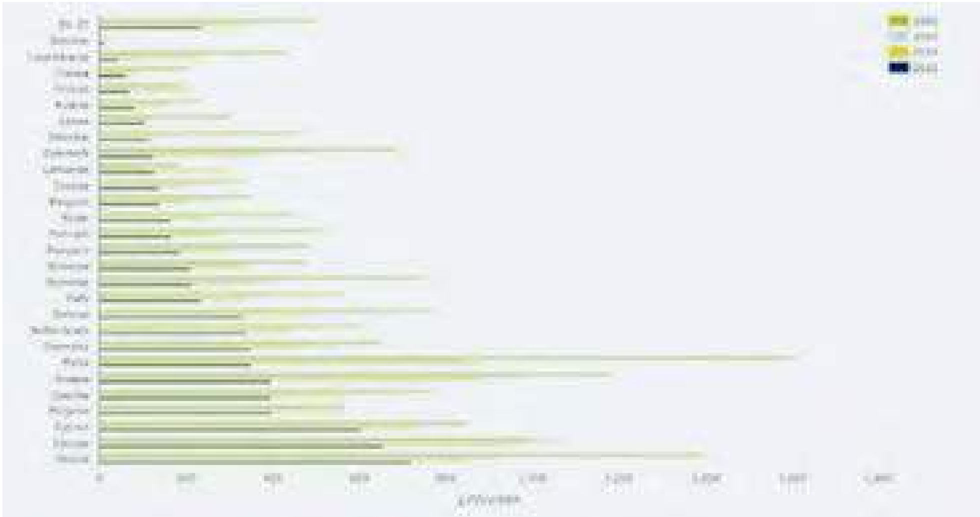

Figure 4. Greenhouse gas emission intensity of electricity generation in Europe. Source: Greenhouse gas emission intensity of electricity generation in Europe (europa.eu), https://www.eea.europa.eu/ims/greenhouse-gas-emission-intensity-of-1

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COUPLING AND COORDINATION ASSESSMENT OF WATER, ENERGY, AND FOOD NEXUS IN INDIA – A SPATIAL SCALE ANALYSIS

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ABSTRACT

Water, energy, and food (WEF) are interrelated and interdependent, forming the WEF nexus. Coupling and coordination degrees, which measure system components' inter-dependence and collaboration, are useful for assessing and managing a region's or nation's WEF nexus. This study used a Coupling Coordination Degree Model (CCDM) to explore the WEF nexus at India's sub-national scale, States and Union Territories (UTs), in 2021 and meet the Sustainable Development Goals (SDGs). The core WEF nexus first established the comprehensive evaluation index and coupling degree, which indicate WEF security progress and interaction, respectively. Next, the degree of coordination indicating governance, collaboration, and cooperation among stakeholders from differ-ent sectors was determined. The comprehensive evaluation index was calculated and coupling degree using 29 indicators based on SDG 2, 6, and 7 was carried out. All Indian States/UTs have a coupling degree of WEF nexus above 0.90, indicating a high-quality connection. 3%, 83%, and 14% of Indian States/UTs showed "quality," "good," and "intermediate" coordinated development, respectively. The developed level of SDG2 is more than SDG6 and SDG7 in most Indian States/UTs. This study also suggests that most States/UTs must effectively implement WEF-related policies and programmes to achieve quality coordinated WEF nexus development. This study may help administrators and policymakers identify States/UTs that need more attention to implement existing or new policies for resource security.

Keywords: WEF nexus, Coupling degree, Coordination degree, Modified Pardee-Rand WEF nexus, Sustainable development goals

1. INTRODUCTION

Water, energy, and food (WEF) security is vital to human well-being and sustainable development. These resources affect people's livelihoods, health, and communities' resilience. The WEF nexus helps explain the complex interactions and trade-offs be-tween these essential resources (Kurian et al., 2018; Srigiri and Dombrowsky, 2022). Energy is needed to pump, treat, and distribute water, whereas agricultural and energy production require water. Agriculture also needs water and electricity. Sector changes might ripple through others. Failure in these sectors might cause water, energy, and food insecurity (Al-Saidi and Elagib, 2017).

The 2011 the Bonn Summit popularised the WEF nexus method (Hoff, 2011). It has become a commonly used paradigm for integrated and sustainable resource planning and management (Kurian, 2017). The WEF nexus is a revolutionary resource manage-ment method that provides WEF security and improves production and utilisation efficiency in social, economic, environmental, and health sectors through cross-sectoral management and cooperation (Jing et al., 2023). The WEF Nexus can help achieve the Sustainable Development Goals (SDGs) and economic growth. The United Nations has proposed 17 SDGs and 169 goals to promote multidimensional balanced development and human society sustainability (Lee et al., 2016). The WEF nexus explicitly links SDG2—zero hunger, SDG6—clean water and sanitation, and SDG7—cheap and clean energy. SDGs are being hampered by a lack of information about

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WEF security, notably accessibility and availability. Many researchers have conducted theoretical and empirical research on the WEF nexus at various scales, analysed it from various theoretical and methodological angles, and created several tools and techniques for simulation and quantitative assessment (Mohtar & Daher, 2016; Yan et al., 2020; Huang et al., 2020; Caputo et al., 2021; Wu et al., 2021; Wen et al., 2022; Mondal, 2023a). Several studies have examined the external mechanism of the WEF nexus, including how it interacts with policy changes (Gain et al., 2015; Albrecht et al., 2018, Mondal et al., 2023a), climate change (Li, 2023), and land use land cover change (Wolde et al., 2021).

The WEF nexus model optimises water, energy, and food resources for efficiency. However, cou-pling and coordinating these sectors helps identify resource optimisation and efficiency opportunities. SDGs and future resource availability depend on WEF nexus connection and cooperation. Li et al. (2012) presented a Coupling Coordination Degree Model (CCDM) to measure sector coordination in complex systems, notably regional sustaina-ble development. The CCDM has been used in urban planning, transportation, environ-mental management, and economic development (Xing et al., 2019; Lu, 2021; Liu, 2022). Coupling means coordinated planning, management, and decision-making across the water-energy-food nexus (Qi et al., 2022). In contrast, coordination in the WEF nexus involves stakeholder collaboration across sectors and governance levels. Coupling and coordination can handle population increase, climate change, water scarcity, energy security, food security, and economic development while promoting environmental sustainability. However, few studies have explored the coupling and coordination of the WEF nexus and advised regional SDG-based research to effectively achieve SDGs within a country. Even though WEF nexus theory and application have advanced, older investigations on its interaction still have limitations. Overall, the research lacks: (1) No studies have linked WEF nexus indices to the Coupling Coordination Degree Model. (2) No research has examined regional WEF nexus coupling and coordination based on SDGs. (3) No study has examined the WEF nexus' coupling and coordination at India's spatial scale (States and Union territories (UTs)). To fill research gaps, this study aims to: (1) Analyse India's sub-national (States/UTs) WEF nexus indices utilising 29 indica-tors based on SDGs 2, 6, and 7 for 2021. (2) Formulate a Coupling Coordination Degree Model using WEF nexus indices and (3) Analyse the degree of coupling and coordina-tion at India's sub-national scale (States/UTs) to provide valuable insights into the interconnections between goals, regional disparities of resources, policy effectiveness, and resource management. This study will aid policymaking, integrated planning, knowledge exchange, and sector conflicts.

2. METHODOLOGY

2.1 Study Area and Data

The study area covers India's 28 states and seven Union Territories (as of 2011), situat-ed between latitude 6° N to 37° 6' N and longitude 68° 7' E to 97° 25' E. According to the most recent estimation of the United Nations (UN DESA, 2023), India is now the world's most populous nation. Except for the northern Himalayas and the western desserts, most Indian states have very dense populations. However, access to essential services such as water, energy and food remains limited for most of the Indian population. The population is expected to be 1.62 billion in 2050, with a projected additional demand of about 30% and 32% for food and water, respectively (OECD, 2017). Additionally, over 880 GW of additional power will be required by 2040 to meet the demand (IEA, 2015). Table 1 shows the secondary data used in this research. Additional data like precipita-tion and evapotranspiration are collected from Indian Meteorological Department (https://mausam.imd.gov.in/) and MODIS and WELD products (https://appeears.earthdatacloud.nasa.gov/), respectively.

2.2 Analysis of Water-Energy-Food nexus indices

WEF nexus indices, like water sub-index (WSI), energy sub-index (ESI), food sub-index (FSI) and WEF nexus index (WEFNI), are calculated using modified Pardee Rand WEF nexus (MPR-WEFN) method (Mondal et al., 2023b). The details of the indicators and equations used to calculate WEF Nexus Index indices are taken from Mondal et al. (2023b). The WSI, ESI and FSI are the evaluation indices of SDG 6 on water security, SDG 7 on energy security and SDG 2 on food security, respectively. A total of 29 indicators concerning SDGs 2, 6 and 7 have been used to calculate the WEF nexus indices.

2.3 Development of Coupling Coordination Degree Model

Energy-Food (WEF) nexus has been accomplished by utilizing the WEF nexus indices. Consequently, the aforementioned model has been employed to examine the level of coupling and coordination within the Water-Energy-Food (WEF) nexus at the States/UTs level in India for 2021. The methodological framework for developing the CCDM is depicted in Figure 1. Firstly, the WEF nexus indices are obtained using the MPR-WEFN method. These indices then determine the comprehensive evaluation index (T). After-wards, the WEFNI and T values are employed to calculate the coupling degree (C). Subsequently, the coordination degree (D) is determined based on T and C.

Table 1 Input data (along with the source) for coupling and degree analysis of WEF Nexus.

SL. No.	Data information	Sources
1	Geographical area	Census of India (2011);
2	Cultivated area	Ministry of Statistics and Programme, Government of India (GoI); National Family
3	Total number of population and age-wise population	https://www.indiastat.com/; https://www.ceicdata.com
4	Total number of farmers	
5	Agriculture worker	
6	Total number of tractors	
7	Number of farmers having access to modern farm equipment	
8	Number of farmers having access to sufficient water and electricity for	
9	% population having access to sufficient water for drinking purpose	
10	% population having access to sufficient water for sanitation purpose	
11	Total number of households	
12	Cropping intensity	Ministry of Agriculture and Farmers Welfare, GoI; https://www.indiastat.com/; https://www.ceicdata.com
13	Crop water productivity of major foodgrain	
14	Average crop productivity of major foodgrain	
15	Cropping intensity of major food grains (paddy, wheat, maize) and vegetable (potato)	
16	Hunger index	Ministry of Statistics and Programme Implementation is a ministry, GoI; https://www.indiastat.com/
17	Food price level index	
18	% population having access to sufficient electricity	Ministry of Power, GoI; Ministry of Petroleum and Natural Gas, GoI; National Family Health Survey-5; https://www.indiastat.com/
19	% household access to modern fuel (like Liquefied Petroleum Gas (LPG))	
20	Total electricity production (renewal and non-renewal)	
21	Egg production	Ministry of Fisheries, Animal Husbandry and Dairying, GoI, National Dairy Development board;
22	Milk production	https://www.indiastat.com/
23	Meat production (poultry, sheep, buffalo, pig)	
24	Fish production	

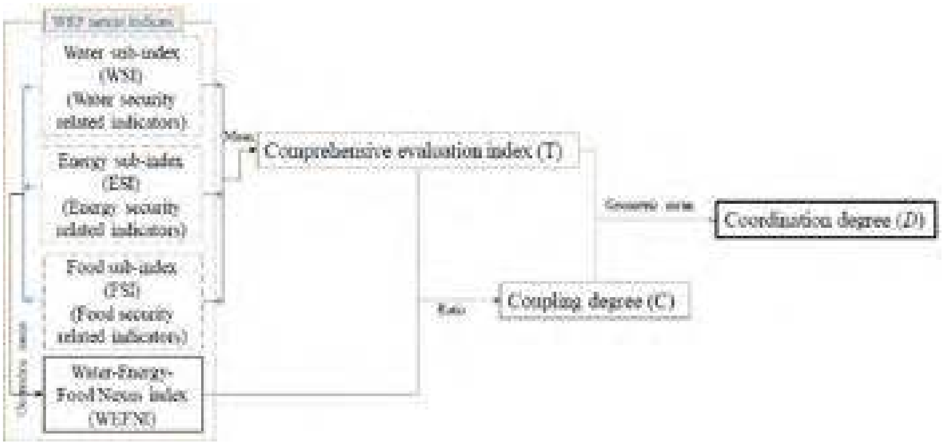

Figure 1. Methodological framework for developing the coupling and coordination degree model of WEF nexus.

2.3.1 Comprehensive evaluation index and coupling degree

The comprehensive evaluation index (T) is basically a way to assess how well different sectors are working together. It takes into account multiple WEF nexus indices to give an overall picture of the coupling and coordination among these sectors. It is calculated using Eq. 1. In the equation, α, β and γ represent the weights of the security of water (SDG6), security of energy (SDG7), and security food (SDG2), respectively. According to van Leeuwen (2017), all the SDGs given by United Nations are equally important; thus, the value of α, β, γ is 1/3 each.

Comprehensive evaluation index $(T) = \alpha \times WSI + \beta \times ESI + \gamma \times FSI = (WSI+ESI+FSI)/3$ (1)

The coupling degree quantifies the interdependence and interconnectedness between the water, energy and food subsystems. It reflects the level of interaction between subsystems, where a higher degree indicates more robust interconnection and vice versa (Luo et al., 2023). Drawing upon sustainable development and coupling coordination theories (Qi et al., 2022; Wang et al., 2023a), the coupling degree relationship was developed as the CCDM component based on WEF nexus subindices. The relationship is as follows:

Coupling degree $(C) = (3 \times \sqrt[3]{(WSI \times ESI \times FSI)})/(WSI+ESI+FSI) = \sqrt[3]{(WSI \times ESI \times FSI)}/((WSI+ESI+FSI)/3) = WEFNI/T$ (2)

Moreover, based on the literature (Qi et al., 2022; Luo et al., 2023), the coupling degree was classified into six classes (Table 2).

Table 2 Classification of coupling degree

Coupling degree (C)	**0.00 – 0.50**	**0.51 – 0.60**	**0.61 – 0.70**
Type	No coupling	Barely coupling	Primary coupling
Coupling degree (C)	0.71 – 0.80	0.81 – 0.90	0.91 –1.00
Type	Intermediate coupling	Good coupling	High quality coupling

2.3.2 Coordination degree

The coordination degree (D) provides insight into how well the water, energy and food sectors are coordinated or integrated within a particular region or context. It is calculated using Eq. 3 and used as the CCDM component. The value of the coordination degree ranges over [0, 1], with a higher value of D indicating increased subsystem coordination and D = 1 being the ideal coupling coordination state (Hu et al., 2022; Luo et al., 2023).

Coordination degree $(D) = \sqrt{(T \times C)} = \sqrt{WEFNI}$ (3)

Using the principle of the rectangle distribution function, the degree of coordination was further classified into four types (Table 3) (Liao, 1999; Ka et al., 2015).

Table 3 Classification of coordination degree

Coordination degree (*D*)	**Type**
0.60 – 0.69	Primary development
0.70 – 0.79	Intermediate development
0.80 – 0.89	Good development
0.90 – 1.00	Quality development

2.4 Comparative analysis of WEF security based on SDGs 6, 7 and 2

Security of Water (SDG6), security of energy (SDG7) and security of food (SDG2) are all connected to each other. They don't exist separately, and they actually have a complicated relationship with one another. If one goal changes, it will impact the other two. During the pursuit of SDGs by countries, the goals can exhibit synergistic or antagonistic relationships with one another. These interactions among the goals, influenced by various external factors, form complex networks and affect the entire socioeconomic and environmental system (Cheng et al., 2023). The comparison coefficients were calculated using equations 4-6 to understand the interplay among these three goals better. Furthermore, the comparison coefficient has been classified into five types (Table 4) (Ka et al., 2015).
Comparison coefficient between Water and Energy (I_we) = WSI/ESI (4)

Comparison coefficient between Energy and Food (I_ef) = ESI/FSI (5)

Comparison coefficient between Food and Water (I_fw) = FSI/WSI (6)

Table 4 Classification of comparison coefficient

Comparison coefficient (*I*)	**Type**
≤ 0.60	Extremely hand-impaired
0.61 – 0.80	Severely impaired
0.81 – 1.00	More shortage
1.01 – 1.50	More adequate
> 1.50	Especially adequate

3. RESULTS AND DISCUSSION

3.1 WEF Nexus indices

The initial step of the WEF nexus CCDM involves calculating WEF nexus indices. Table 5 presents the values of the Water Security Index (WSI), Energy Security Index (ESI), Food Security Index (FSI), and WEF Nexus Index (WEFNI) for various Indian States/UTs. Figure 2 illustrates the spatial variation of water, energy, and food sub-indices in India for the year 2011. The indices are categorised into five levels: very low (0.00-0.30), low (0.31-0.50), medium (0.51-0.70), high (0.71-0.90), and very high (0.91-1.00). Examining Table 5 reveals that Delhi has the highest WSI (0.98), indicating 98% water security. In contrast, Lakshadweep has the lowest WSI of 0.41, indicating a lack of water availability and uni-versal access. Except for Chandigarh and Lakshadweep, all States/UTs have a WSI above 0.50, indicating progress towards achieving water security. Around 22% of the States/UTs have a medium WSI, while 72% have a high WSI (Fig. 2(a)). Delhi has the highest ESI of 0.88, indicating not fully energy secure. Conversely, West Bengal has the lowest ESI at 0.72 due to limited access of clean energy. Around 58% of the States/UTs have a high ESI, while 42% have a medium ESI (Fig. 2(b)). According to India Energy Outlook 2021 report, India has seen extraordinary successes in its recent energy development, but many challenges remain, and the Covid-19 pandemic has been a major disruption. Andhra Pra-desh has taken the lead with the highest FSI of 0.98, while Delhi lags behind with the low-est FSI of 0.46 (Table 5). However, all States and UTs have FSI values above 0.50, indicat-ing progress toward achieving food security, with around 90% and 8% of States/UTs at-tained a high and very high FSI, respectively (Fig. 2(c)). The overall WEF security, repre-sented by WEFNI, is highest in Andaman & Nicobar (0.89) and the lowest in Lakshadweep (0.63) (Table 5). Most States/UTs have a high WEFNI (Fig. 2(d)). In 2021, India's overall WSI, ESI, FSI, and WEFNI were 0.75, 0.72, 0.80, and 0.76, respectively.

3.2 Comprehensive evaluation index

The comprehensive evaluation index (T) mainly depends on WEF sub-indices and a higher T shows a greater overall WEF security (Qi et al., 2022). Table 5 presents the values of the comprehensive evaluation index for the Indian States/UTs. It is evident from Table 5 that Andaman & Nicobar recorded the highest comprehensive evaluation index (0.89), while Chandigarh had the lowest (0.65). The comprehensive evaluation index displays substan-tial variation across the States/UTs, with an average T of 0.76 in 2021 for India.

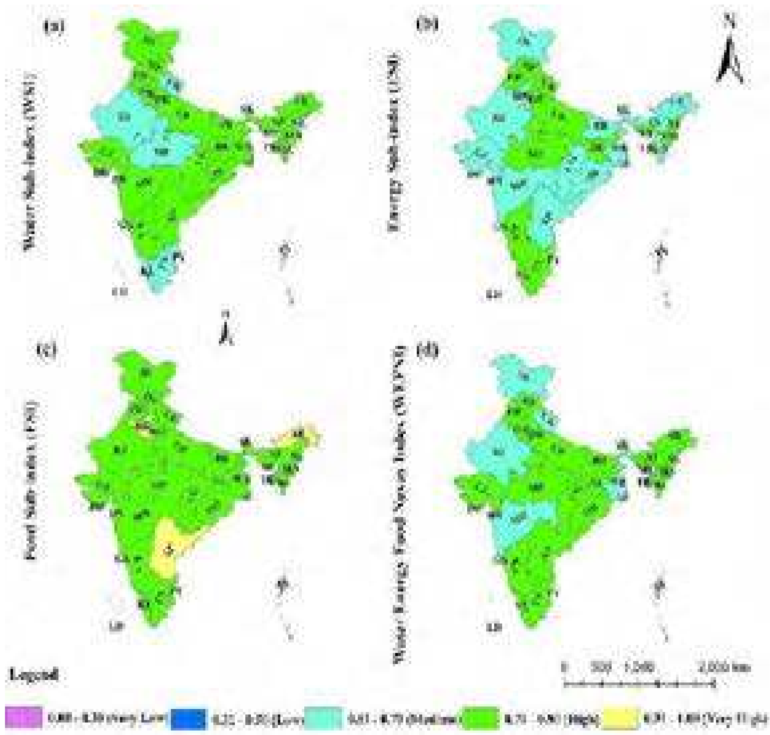

Figure 2. Spatial variation of WEF nexus indices and their degree in Indian State/UTs for 2021: (**a**) Water Sub-index (WSI), (**b**) Energy Sub-index (ESI), (**c**) Food Sub-index (FSI), (**d**) Water-Energy-Food Nexus Index (WEFNI).

3.3 Coupling and coordination degree analysis

The coupling and coordination degrees of the WEF Nexus in States/UTs have been calcu-lated using the CCDM and included in Table 5. Table 5 shows that the coupling degree across States/UTs is above 0.90. The high coupling level suggests a strong correlation between the three resources, i.e., WEF (Qi et al., 2022; Luo et al., 2023). The variation of coupling degree across States/UTs is significantly less.

Figure 3 presents the coordination degree of various States/UTs, classified from interme-diate development to a quality development level. Figure 3 shows that around 83% of States/UTs have good development and 14% have ‘quality development’ coordination degrees. Besides, Andaman & Nicobar have the highest coordination degree at 0.95, showing a ‘quality development’ coordination degree. In contrast, Kerala has the lowest coordination degree at 0.79, reflecting an ‘intermediate development’ coordination stage. Besides Andhra Pradesh, Dadra & Nagar Haveli, Goa, Haryana and Puducherry have quali-ty development, and the rest of the States/UTs have ‘good development’ coordination degrees. While WEF nexus indices provide an ordering of States/UTs based on security, the coupling and coordination degrees offer a measure of the level of development in WEF security. Therefore, the coupling and coordination degrees are more prominent in assessing WEF security than the WEF nexus indices.

By examining the coupling and coordination degree levels, it becomes evident that the coupling degree surpasses the coordination degree in all States/UTs. The values indicate that the level of interaction between the WEF is stronger than the quality of coordinated development (Wang et al., 2022). Therefore, the government agencies, stakeholders, and policymakers must focus on implementing new policies and schemes for increasing the coordination development of the WEF nexus in most States/UTs, but more so in the States/UTs having low to intermediate development. In the long run, implementing actions that prevent ineffective and unsafe utilisation of water, energy, and food resources are essential, as this could negatively impact the system's security, coupling, and coordinated development (Wang et al., 2023b).

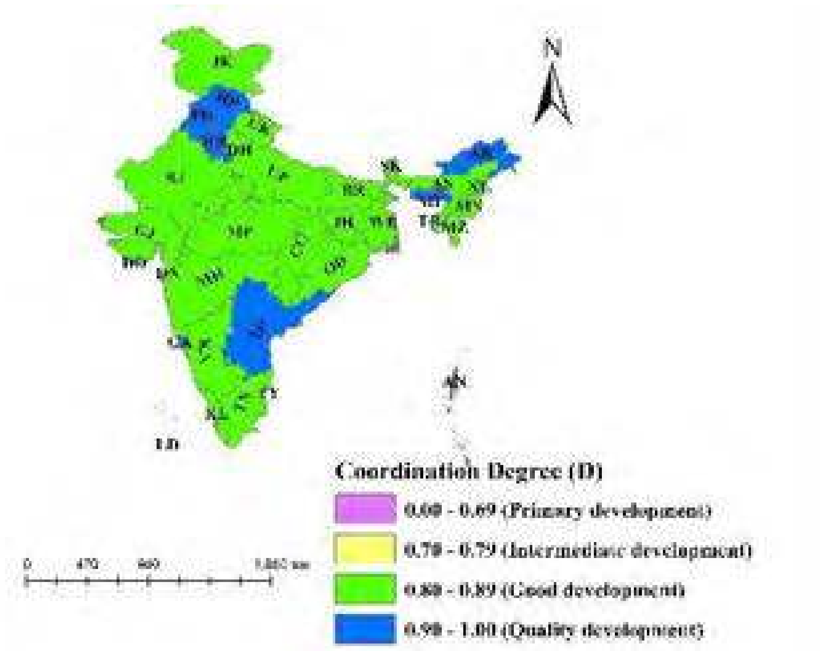

Figure 3. Coordination degree of Indian States/UTs.

3.4 Comparative relationship analysis of WEF security

The comparative relationship analysis between Water-Energy, Energy-Food and Food-Water examines the interactions and trade-offs between water, energy, and food systems in different contexts (Fig. 4). Figure 4 (a) shows the spatial variation of the comparison coefficient between water-energy security in the States/UTs. From Figure 4, it is evident that 64% of States/UTs have $I\_we>1$, indicating better development of the water system (SDG 6) than the energy system (SDG 7), mainly due to the higher amount of water availability. Fig. 4(a) also shows that Lakshadweep has I_ef lower than 0.60, reflecting an 'extremely hand-impaired' condition. In contrast, Chandigarh, Himachal Pradesh, Jharkhand, Karnataka, Kerala, Madhya Pradesh, Nagaland, Puducherry, Rajasthan, Sikkim, Tamil Nadu and Uttarakhand have I_ef varying between 0.81 and 1.0, suggesting a 'more shortage' type of water-energy comparison coefficient. Figure 4(b) shows the comparison coefficient between energy-food, varying from 'severely impaired' to 'especially adequate' level in the States/UTs. Most of the States/UTs (88%) have $I\_ef<1$ suggesting that the food system (SDG 2) is outperforms

Table 5 Water-Energy-Food Nexus Indices Comprehensive Evaluation Index (T), Coupling degree (C) and coordination degree (D) of Indian States/UTs

State / UTs	WSI	ESI	FSI	WEFNI	T	C	D
Andaman and Nicobar Islands	0.94	0.87	0.87	0.89	0.89	1	0.95
Andhra Pradesh	0.79	0.69	0.98	0.81	0.82	0.99	0.9
Arunachal Pradesh	0.83	0.64	0.97	0.8	0.81	0.98	0.89
Assam	0.82	0.63	0.82	0.75	0.76	0.99	0.87
Bihar	0.84	0.68	0.8	0.77	0.77	1	0.88
Chhattisgarh	0.84	0.7	0.79	0.77	0.78	0.99	0.88
Chandigarh	0.49	0.7	0.77	0.64	0.65	0.98	0.8
Daman and Diu	0.93	0.86	0.82	0.87	0.87	1	0.93
Delhi	0.98	0.88	0.46	0.73	0.77	0.94	0.85
Dadra and Nagar Haveli	0.78	0.74	0.79	0.77	0.77	1	0.88
Goa	0.85	0.74	0.89	0.82	0.83	0.99	0.91
Gujarat	0.75	0.7	0.81	0.75	0.75	1	0.87
Himachal Pradesh	0.77	0.81	0.81	0.8	0.8	1	0.89
Haryana	0.87	0.69	0.97	0.84	0.84	1	0.92
Jharkhand	0.75	0.79	0.79	0.78	0.78	1	0.88
Jammu and Kashmir	0.78	0.57	0.77	0.7	0.71	0.99	0.84
Karnataka	0.71	0.74	0.79	0.75	0.75	1	0.86
Kerala	0.65	0.75	0.75	0.72	0.72	1	0.85
Lakshadweep	0.41	0.84	0.71	0.63	0.65	0.96	0.79
Maharashtra	0.76	0.57	0.78	0.7	0.7	1	0.84
Meghalaya	0.84	0.73	0.81	0.79	0.79	1	0.89
Manipur	0.72	0.71	0.73	0.72	0.72	1	0.85
Madhya Pradesh	0.7	0.71	0.76	0.72	0.72	1	0.85
Mizoram	0.78	0.69	0.81	0.76	0.76	1	0.87
Nagaland	0.69	0.71	0.79	0.73	0.73	1	0.85
Odisha	0.83	0.67	0.83	0.77	0.78	0.99	0.88
Punjab	0.82	0.73	0.87	0.8	0.81	0.99	0.89
Puducherry	0.83	0.85	0.82	0.83	0.83	1	0.91
Rajasthan	0.52	0.64	0.81	0.65	0.66	0.99	0.81
Sikkim	0.65	0.74	0.79	0.72	0.73	0.99	0.85
Tamil Nadu	0.62	0.79	0.8	0.73	0.74	0.99	0.85
Tripura	0.74	0.74	0.79	0.76	0.76	1	0.87
Uttarakhand	0.56	0.76	0.81	0.7	0.71	0.99	0.84
Uttar Pradesh	0.81	0.75	0.81	0.79	0.79	1	0.89
West Bengal	0.73	0.55	0.8	0.68	0.69	0.98	0.82

that of the energy system (SDG 7). However, Daman and Diu, Delhi, Lakshadweep and Puducherry have $I_{ef}>1$ reveals that the progress in the energy system (SDG 7) outperforms that of the food system (SDG 2). Most of the States/UTs under the 'severely impaired' (22%) and 'more shortage' (61%) type of energy-food comparison coefficient. Only Delhi is under the 'especially adequate' and Daman and Diu, Lakshadweep and Puducherry are under the 'more adequate' type of I_{ef}. In the case of the food-water comparison coefficient (Fig. 4(c)), around 67% of States/UTs have $I_{fw}>1$, indicating that the development of the food system (SDG 2) is better than that of the water system (SDG 6).

Around 55% and 25% of States/UTs have a 'more adequate' and 'more shortage' type of food-water comparison coefficient, respectively. Therefore, from the comparison coefficient, we can infer that food security in most States/UTs is the most stable (although not entirely sufficient), followed by water and energy security. Although there is an interconnection among the three SDGs, the linkages between SDG 6 and 7 and SDG 2 and 7 need special attention (Cheng et al., 2023), as energy is necessary for food production and water usage. Therefore, focusing on the development and efficient use of energy for long-term sustainable development is essential. However, the food and water sectors should also have sustainable development strategies. All three SDGs must work in an integrated way to minimise the adverse effects on others.

3.5 Policy recommendation

The coupling and coordination degrees of the WEF nexus indicate the level of develop-ment within the WEF system, specifically related to SDGs 6, 7, and 2, in States/UTs. In order to attain sustainable development of WEF resources in the country, States/UTs with high coupling and coordination degrees must participate and contribute actively.

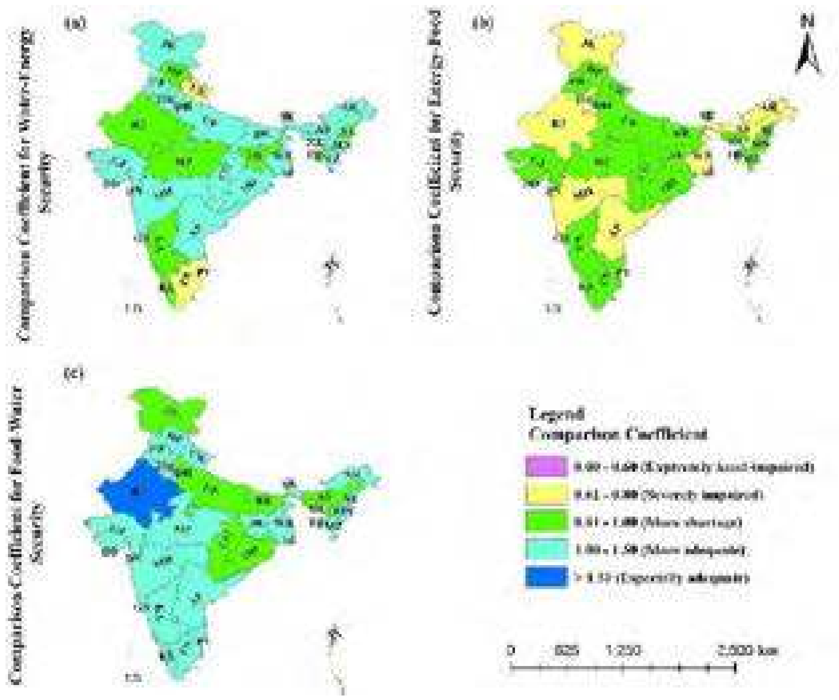

Figure 4. Comparison coefficient of (**a**) Water-Energy (**b**) Energy-Food (**c**) Food-Water security for Indian State/UTs.

Their ac-tive involvement is essential for achieving the desired outcomes regarding the sustainable development of WEF resources. In regions characterised by limited or inadequate water resources, such as southern (Kerala, Lakshadweep and Tamil Nadu), western (Rajasthan), Northern (Chandigarh), central (Uttarakhand) and north-eastern (Nagaland and Sikkim) States/UTs of India, it is imperative to enhance investment in scientific and technological advancements to bolster water security. The development of largescale water harvesting structures, design of low-cost water harvesting structures for rural households, use of wa-ter-saving technology for agriculture (e.g., drip and sprinkler irrigation), reuse of household and industrial water, the establishment of wastewater treatment plants, installation of solar lift irrigation, deep tube wells, household tap water connection and sanitation could be the viable options (Ashoka et al., 2015; Islam et al., 2017; Tortajada, 2020; Cheng et al., 2023). In urban areas, implementing individual rooftop rainwater harvesting and wastewater recycling for vehicle washing, gardening, and agriculture could enhance water security (Chapagain et al., 2022).

The states/UTs with insufficient energy resources, especially insufficient energy resources, especially, Jammu & Kashmir, Maharashtra, Mizoram, Andhra Pradesh, Odisha, Arunachal Pradesh, Bihar, Rajasthan, Haryana, West Bengal and Assam, need energy security-related policy intervention. Increasing solar energy production by installing solar panels in institutions and administrative units and deploying solar streetlights in rural and urban are-as may address the energy needs (Mondal et al., 2023a). Additionally, efforts should be made to enhance hydropower and wind energy production by installing hydropower and wind power systems in suitable locations across the country. Promoting nuclear power plants, installation of biogas power plants in rural areas, providing electricity and LPG gas connections to each rural household, providing solar lift irrigation setup to farmers, instal-lation of solar power drip irrigation, accessibility of affordable farm equipment and ma-chinery to farmers through Farmers Producer Organisation (FPO) and custom hiring cen-tres may also be included in the long-term strategy to address energy issues (Alaofè et al., 2016; Dawn et al., 2019; Majid, 2020, Vijayakumar, 2020, Sanchez et al., 2023).

Moreover, all the states/UTs except Delhi have a high and very high level of food security but not a hundred per cent sufficiency. Therefore, the government has to focus on improv-ing food security in these States/UTs by implementing different policies focussing on im-proving agricultural production, formation of FPOs on the regional scale, introducing high-yielding crop varieties through FPOs, popularising modern farm equipment and mi-cro-irrigation, accessibility of affordable irrigation water for farmers, enhancing food stock by developing cold storage in villages, and expanding the network of fair-prices food stores (Pandey, 2015; Vijayakumar, 2020; Devkota et al., 2020; Wang et al., 2021; Jatav et al., 2022; Mondal et al., 2023a).

Moreover, the government should optimise energy output and increase renewable energy R&D to address and strengthen food-energy and water-energy relationships. Additionally, it is crucial to focus on reducing energy-related environmental damages by adopting cleaner and more sustainable energy sources, implementing energy-efficient technologies, and implementing environmental regulations (Cheng et al., 2023). Solar power-based or solar power IoT-based drip irrigation systems could be propagated to enhance food and energy security (Burney et al., 2010; Barman et al., 2020).

4. CONCLUSIONS

The WEF nexus sustains life, and its interdependence is essential for SDGs. India's WEF nexus management is complicated by population increase, urbanisation, and industrializa-tion. Thus, assessing WEF sector coupling and coordination is crucial to SDG manage-ment and achievement. Based on SDGs 2, 6, and 7, the study established a coupling co-ordination degree model (CCDM) to assess coordinated development and measure WEF security quantitatively and qualitatively. In 2021, India's sub-national WEF Nexus assess-ment revealed useful insights into the WEF sectors' coupling and coordination degrees.

Results showed that WEF security in Indian States/UTs varies. However, all States/UTs had strong WEF nexus coupling. WEF subsystems interact and depend due to high cou-pling. State/UT coordination ranged from "intermediate" to "quality." 83% of regions had 'good' development coordinated degree, while the rest had 'moderate' development. To reduce negative effects on each other, energy, water, and food sectors must recognise their interconnection and prioritise sustainable growth. Overall, coupling and coordination assessments help evaluate and manage the WEF nexus. It emphasises the need for holis-tic and integrated approaches to WEF security, contributing to India's SDGs. By highlight-ing coupling and coordination in the WEF nexus, societies can improve resource man-agement.

This study's limitation is the comprehensive evaluation index's equal weighting of all indi-cators. Entropy and hierarchical analysis have been used to weight indicators for WEF nexus coupling coordination analysis. This study examined WEF nexus coupling and co-ordination degrees in Indian States/UTs using only one year of data, neglecting develop-ment trends. Future research should address this constraint by assessing coupling and coordination degrees for numerous years, considering the WEF system's evolution, to improve policy implementation towards the SDGs.

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FOOD SECURITY STATUS AND INCOME GENERATION: A CASE STUDY OF THE AGRI-SILVICULTURE IN SOUTH AFRICA

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ABSTRACT

Agroforestry is a land use system that includes the use of woody perennial and agricultural crops and animals in combination to achieve beneficial ecological and economical interactions for food, firewood, fodder and fertilizer. The Limpopo Province's average annual rainfall is 600 mm and the threshold for rainfall agriculture is averaged at 250 mm annually. In terms of forestry, the plantation forests of South Africa use just 3% of the country's total water resources and rainfall needs to be higher than 750 mm per annum to sustain commercial forestry. The overall aim was to determine the status of the agri-silviculture community growers in terms of income generation and food security. The major objectives were: (1) to identify and describe the socio- economic characteristics of the selected agri-silviculture community growers; (2) to determine and compare the 3-year food security status and food insecurity levels among agri-silviculture community growers; (3) to determine and compare the 3-year income generation among agri-silviculture community growers. A purposive sampling technique was used to select 136 agri-silviculture (Groundnuts and Eucalyptus Tree) community growers. Quantitative and qualitative designs were used as a questionnaire written in English, stakeholder's discussion and field observations were part of the data collection. Decadal (ten-day period) 1km X1km surfaces were created from rainfall data downloaded from the AgroMet databank at the Agriculture Research Council –Institute of Soil, Climate and Water (South African Weather Service and ISCW weather stations) from stations with a period of 10 years or more. The socio-economic data was also coded, captured and analysed using Statistical Package for Social Science (SPSS version 21).

The future rainfall estimates results were as follows: (33rd, median and 66th percentile annual rainfalls) indicated the estimates of rainfall in the future years. The results also indicated that agri-silviculture community growers' food insecurity was flattened year after year and 100% food security achieved at year 3. In addition, another trend established is that groundnuts quantity increases by +300bags (300*50kg/bag = 15000kg) each growing season and groundnuts prices increases by +R (South African Rands) 100 each growing season. In addition, the results covered the energy element of the agroforestry practice as the rural communities are getting firewood from the plantation for cooking due to lack of electricity. In fact, due to the current electricity load shedding in South Africa, firewood from the plantations is in demand now for the rural communities staying near the plantations. It is concluded that recognizing and tackling the main factors, both socioeconomic and biophysical consideration, that determine participation of farmers in agroforestry are essential for the adoption of agroforestry. Hence, it is recommended that agroforestry practice should be intensified across all South African Forestry Company Limited (SAFCOL) plantations as it is contributing to food security, income generation, market access and sustainable communities' livelihoods.

Keywords: Agri-silviculture, Food Security, Income Generation, South Africa

INTRODUCTION

Agroforestry is a land use system that includes the use of woody perennial and agricultural crops and animals in combination to achieve beneficial ecological and economical interactions for food, fibre and livestock production. Properly managed agroforestry systems provide multiple benefits and contribute to improved livelihoods and income generation. Agroforestry

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1 United States Dollar (USD) = R 18.75

systems are also area and climate specific hence, it is a key to develop agroforestry systems that are locally relevant and consider the biophysical and socio-economic context on a case-by-case basis. South Africa is known as a semi – arid country vulnerable to water stress, particularly drought.

In addition, agri-silviculture is a system where there is a combination and integration of crops and trees and managed on the same landscape. According to Norgrove (2008), Bentrup et al. (2019) and Maponya et al. (2022) the main advantages of the agri-silviculture system are as follows: (1) Produce multiple products such as food/vegetables/fruits, fodder and forage needed for livestock, fuel wood, timber, and leaf litter needed for organic manure production (2) Improve and sustain the crop productivity which increases the level of income of the farmers (3) Improve the nutritive value of animal feed due to the supply of green fodder (4) It's the best practice for soil nutrient recycling, which also helps to reduce chemical fertilizer purchase (5) Improve the farm site ecology by reducing surface run off, soil erosion and nutrient loss, gully formation and landslides (6) Improve the local micro-climate and enhance the productive capacity of the farm (7) Reduce pressure on forests for fodder, fuel wood and timber (8) It helps for the beautification of the surrounding areas.

The Limpopo Province's average annual rainfall is 600 mm and the threshold for rainfall agriculture is averaged at 250 mm annually. In terms of forestry, the plantation forests of South Africa use just 3% of the country's total water resources and rainfall needs to be higher than 750 mm per annum to sustain commercial forestry. The parts of Limpopo where plantations and woodlots have been established historically, have rainfall that well above the annual average for the province, as well as agricultural and forestry production thresholds. Thus the area has seen the integration of crops including maize, sweet potatoes, groundnuts and Bambara groundnuts into stands of eucalyptus trees (Maponya et al. 2020).

According to MDM (2014) agriculture and forestry plays an important role for economic growth in terms of employment and land use in the Mopani District. Mopani district contributed significantly towards the activity of agriculture on the provincial level (MDM, 2014). About fifty percent of the farm income in Limpopo province in horticulture is earned in this district. The most important crops in terms of monetary value are citrus, vegetables and subtropical fruits. About six to seven percent of the land can be considered arable of which 43% is under irrigation in the Mopani District (MDM, 2014). In addition, forests stretch northwards and eastwards of Tzaneen are a major source of pine and eucalyptus timber. The Mopani district, and especially the town of Tzaneen, has a large number of sawmills which form an important part of the regional economy, providing a base to drive other subsectors (MDM, 2014).

A study conducted in the Limpopo and Mpumalanga Provinces, South Africa by Maponya et al. (2020), addressed the food security index indicators; (1) Availability (Sufficient) (2) Accessibility (Physical, Social & Economic Access) (3) Utilisation (Dietary Needs, Safe & Nutritious) (4) Stability (Short Term) (5) Sustainability (Environmental, Social & Economic) (6) Agency (People & Food Preferences).The study used standard questionnaire to ask participants to address food security status (percentage food secure/insecure) and levels (Severe, Mild & Moderate). The study determined the food security status of the respondents before South African Forestry Company Limited (SAFCOL), Department of Environment, Forestry and Fisheries (DEFF) and Mountain To Ocean (MTO) allocated land, provided production inputs and paid stipends and found that the food insecurity percentage was at +65%. The food security status was assessed after the intervention. i.e., after growers had harvested groundnuts, Bambara nuts, maize, vegetables. It was found that most growers used the harvest for household consumption while some managed to sell in the informal markets i.e., toll gates, pension pay points, outside towns, within their villages, etc. According to Maponya et al. (2020) the inclusion of crop production contributed to the flattening of the food insecurity curve and improved the communities' livelihoods as the final food insecurity percentage stood at 20% and most community growers fell in the mild and moderate categories.

In the present study, research was conducted with the overall aim to determine the status of the agri-silviculture community growers in terms of income generation and food security. The major objectives were: (1) to identify and describe the socio- economic characteristics of the selected agri-silviculture community growers. (2) to determine and compare the 3-year food security status and food insecurity levels among agri-silviculture community growers (3) to determine and compare the 3 year income generation among agri-silviculture community growers.

METHODS

2.1 Study Area

A total of 136 agri-silviculture community growers participated in the study and were spread on the SAFCOL JDM Keet plantation as indicated in Figure 1. Furthermore, according to ARC (2020) the relatively narrow escarpment area in the district receives an annual rainfall of 800 to more than 1000 mm. A narrow band of relatively high rainfall (700-800 mm p.a.) runs along the foot of the escarpment. The broad lowveld plain (area below 1000m above sea level) receives 400-600 mm p.a. The rainfall is very strongly concentrated during the summer months. Summer temperatures are high over the lowveld (Tmax in January: 31-34°C). Winter temperatures are mild over the lowveld (Tmin in July: 7-10°C). Regular frost does not occur in the lowveld. Fairly large tracts of moderately deep to deep, well drained loam or clay loam soils are found in the Tzaneen area, the alluvial valleys of the major rivers, a belt between Tzaneen and Phalaborwa. There is thus an overabundance of good soils in comparison to the water availability situation.

2.2 Study Design

The research employed both qualitative and quantitative methods concurrently and this was applied with the aim on establishing the limitations, balance and strength of the data. Furthermore, the methods included participatory action research as the community growers and stakeholders benefitted while the research was ongoing. Data collection methods were via tele - interviews, site observations, past research, web and governmental reports. Pre- and post-intervention questionnaire was developed, and pilot tested with researchers working on community development within the Agricultural Research Council (ARC). A closed and open-ended questionnaire with the following sections was used: socio-economic, food security, sustainability, perceptions, market information and observations. Closed-ended questions provide a question immediately and ask participants to choose from a list of possible responses and are quantitative in nature, allowing the researcher to gather numerical data for statistical analysis and it took maximum 20 minutes to interview each community grower. Open-ended questions alternatively are those that provide participants with an allowance to construct their own response about the subject matter. The latter will include focus group discussions and field observations. The ARC & SAFCOL team conducted face to face interviews on the same 136 community growers yearly over a 3- year period (2020/21; 2021/22 and 2022/23 growing seasons). The 136 community growers were interviewed in their own native language for better understanding. Agricultural Research Council (ARC) technicians were recruited and trained on the PAR (Participatory Action Research) approach and data collection and analysis.

2.3 Sampling Procedure and Analytical Technique

A purposive sampling technique was used on selected 136 agri-silviculture community growers in the Mopani district during the 2022/23 growing season. A rule of thumb was applied, which is the minimum selection of 10% of the population (estimated 500 agri-silviculture community growers) and it is considered as a good sample size. These agri-silviculture community growers were spread on the 70 ha South African Forestry Company Limited (SAFCOL) land and each agri-silviculture community grower was allocated an area of land as follows for production (in m^2): 70ha*10000 m^2 (700 000m^2) of land to 500 growers, with each grower receiving 1400m^2 (700000m^2/500). The list of agri-silviculture community growers were supplied by SAFCOL and the sample size was agreed with the stakeholder. Eucalyptus trees were then integrated with groundnuts. Furthermore, data collected was analyzed quantitatively using the Statistical Package for Social Sciences (SPSS) windows version 21. Descriptive analysis was conducted.

In addition, the study employed the following food security indicators: Food Availability, Food Accessibility and Food Diversity. The community growers were also categorized as follows: (1) **Food secure:** Community growers did not worry about food access; they rarely experienced anxiety about not having enough food. These are community growers that were able to have a full meal three times in a day without food running out, in the past 30 days. (2) **Mildly food insecure:** Community growers were anxious about not having sufficient food. They usually consumed an inadequate diet or ate food that they did not prefer. These community growers experienced food insecurity once or twice in the past 30 days (3) **Moderately food insecure:**

Community growers began sacrificing quality on a continuous basis by consuming an inadequate diet and eating less preferred food. They started reducing the quality of food intake by decreasing meal sizes. These community growers experienced food insecurity three to ten times in the past 30 days (4) **Severe food insecure:** Community growers experienced high incidences of food insecurity. The condition of reducing meal sizes and the number of meals worsened each day. The three most severe conditions of going a whole day without eating, going to bed hungry or running out of food in the past 30 days occurred often. These community growers experienced food insecurity more than ten times in the past 30 days.

2.4 Average Monthly Rainfall Approach

Decadal (ten-day period) 1km x1km surfaces were created from rainfall data (1920 – 1999) downloaded from the AgroMet databank at the Agricultural Research Council- Soil, Climate and Water (ARC-SCW) (South African Weather Service and SCW weather stations) from stations with a recording period of 10 years or more. Regression analysis and spatial modelling were utilized taking into account topographic indices such as altitude, aspect, slope and distance to the sea during the development of the surface.

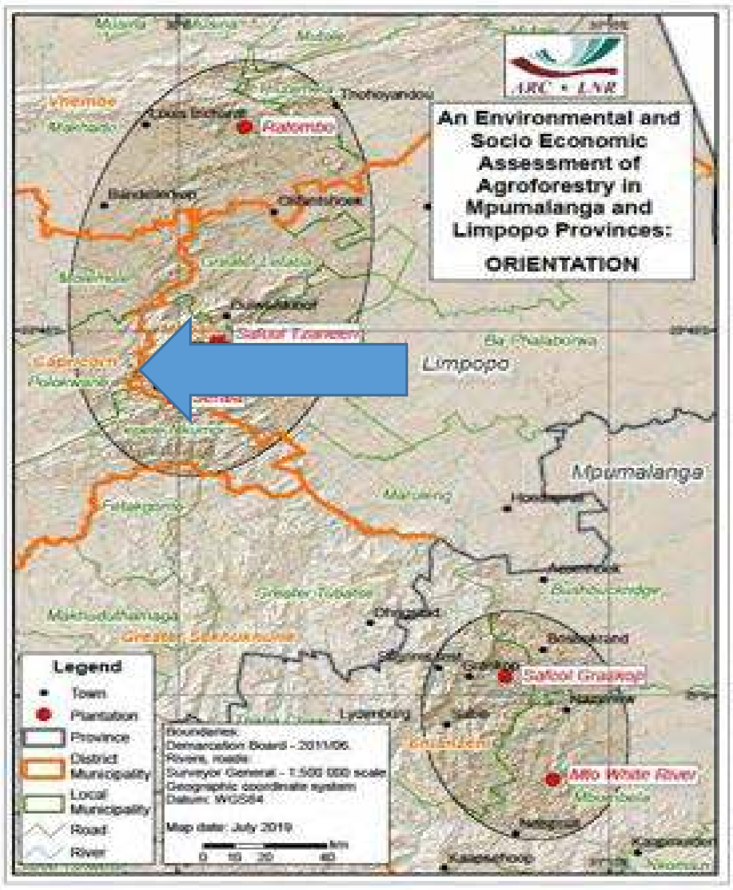


Figure 1: SAFCOL JDM Keet and other agroforestry sites.

RESULTS AND DISCUSSION

3.1 Agri-silviculture Community Growers Selected Socio-Economic Characteristics

The majority of agri-silviculture community growers interviewed were female. According to Table 1, 66% of women were interviewed as compared to 34% males. In terms of educational attainment (Table 1), 83% of growers had less than grade 7 education and 15% of growers had matric education. In addition, the community growers indicated that for agroforestry practice they relied mostly on their indigenous knowledge system (IKS) hence 74% did not receive any formal training. Results on land acquisition (Table 1) indicated that the growers were allocated land by SAFCOL for production. The age distribution of the growers indicated that the majority were in the age group of >60 (62%). As indicated in Table 1, there is 2% of youth involvement, 36 – 45 while 34% were in the 46 – 60 year group. This situation is worrisome and indicates the urgent need to attract the young generation into agroforestry as an important priority. The same trend of youth involvement was observed in the Limpopo and Mpumalanga Provinces (Maponya et al., 2019; Maponya et al., 2020; Maponya et al., 2021). The agri-silviculture community growers' agroforestry experience is spread 2% of the growers had 1 to 5 years of experience; 2% had 6 to 10 years; 34% had 11 to 20 years and 62% had 21 to 49 years of experience. Another interesting trend was the participation of agri-silviculture community growers from other districts i.e., Capricorn and Vhembe.

Table 1: Agri-silviculture Community Growers Selected Socio Economic Characteristics

Variables	Community Growers	% Community Growers Socio-Economic Characteristics
Province		
Limpopo	136	100
District		
Mopani	132	97
Capricorn	3	2
Vhembe	1	1
Total	136	100
Gender		
Female	90	66
Male	46	34
Total	136	100
Age Categories		
18 – 35	3	2
36 – 45	3	2
46 – 60	46	34
>60	85	62
Total	136	100
Level of Education		
Less Grade 7	113	83
Matric	20	15
Post Matric	4	2
Other	0	0
Total	136	100
Land Acquisition		
SAFCOL Land	136	100
Total	136	100
Agroforestry Experience		
1 - 5	3	2
6 - 10	3	2
11 - 20	46	34
21 - 49	85	62
>50	0	0
Total	136	100
Training Provided		
Yes	36	26
No	100	74
Total	136	100

3.2 Agroforestry sites rainfall availability future estimates

The three estimate rainfall maps (Figures 2 to 4) show the 33rd percentile, median (50th percentile) and 67th percentile. To explain what these maps depict, one can consider the 33rd percentile. If there were 100 years of recorded data arranged in sequence from dry to wet, then the 33rd percentile would be the value of the 33rd year. In other words, the chances are good to exceed this rainfall, or the chances are small that you will have less rain. The model estimated annual rainfall for the broad study area at 801 – 1000+ mm for the 33rd percentile; 901 – 1000+ at the 50th percentile and +1000mm at the 67th percentile. These agroforestry sites will allow production of all components (Trees, Crops, Livestock and Pasture) and will thus support agroforestry.

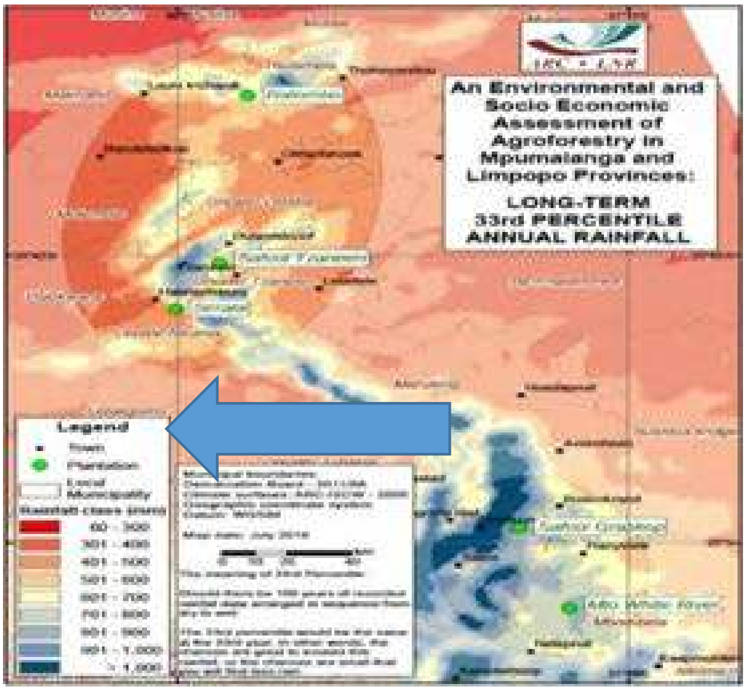


Figure 2: Limpopo and Mpumalanga Provinces long-term 33rd percentile annual rainfall (ARC-SCW, 2020)

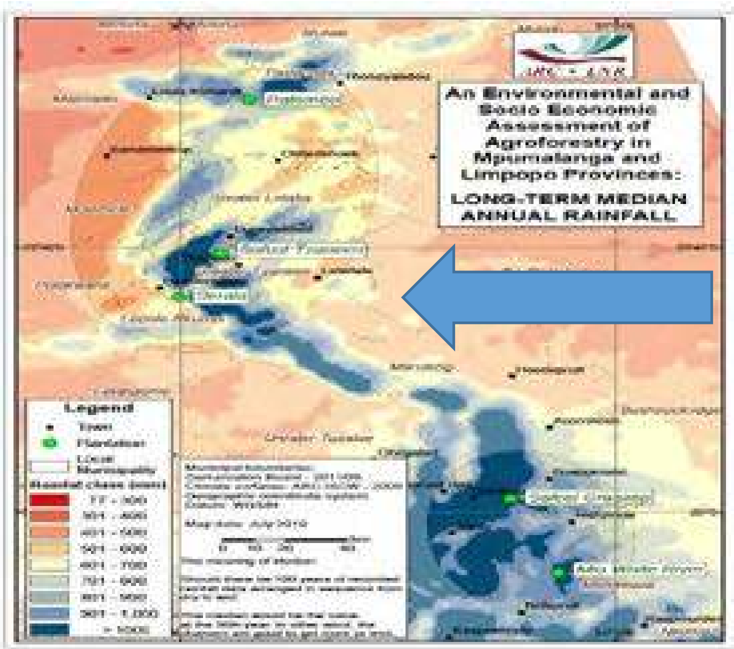


Figure 3: Limpopo and Mpumalanga Provinces long-term 50th percentile annual rainfall (ARC-SCW, 2020)

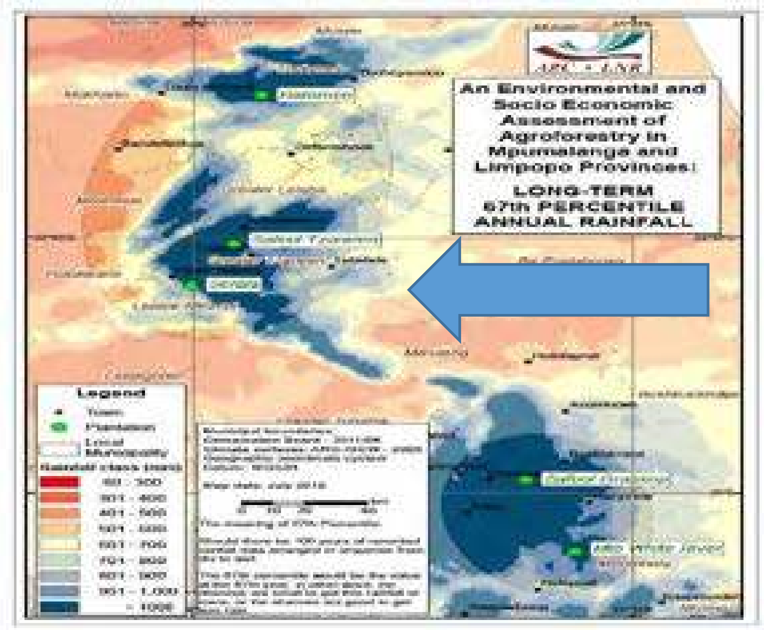


Figure 4: Limpopo and Mpumalanga Provinces long-term 67th percentile annual rainfall (ARC-SCW, 2020)

3.3 Agri-silviculture Community Growers Food Security and Food Insecurity levels (3 growing seasons' comparisons)

3.3.1 Food Security and Food Insecurity Levels during the 2020/21 growing season

3.3.1.1 Food accessibility during the 2020/21 growing season

In terms of food accessibility: 136 agri-silviculture community growers indicated that they do not have resources like land to grow or access food and Table 2 indicates the food insecurity levels among 136 agri-silviculture community growers were moderately food insecure. Furthermore, the agri-silviculture community growers indicated that they resorted to monotonous diets because it is all that they can afford. For instances, 136 agri-silviculture community growers sometimes have to eat fewer meals in a day, 136 agri-silviculture community growers sometimes have to eat a smaller meal, 136 agri-silviculture community growers sometimes eat some foods that really did not want to eat. This food access situation is worrying however the community growers indicated they don't go day and night without eating. This study is similar to a community-based cross-sectional study conducted in Ethiopia on 392 households under agroforestry environment. The study finds a high prevalence of household food insecurity in the first year and declining food insecurity levels in the next years (Desalegn and Jagiso, 2022).

Table 2: Agri-silviculture Community Growers Food Security Levels & Extent of Food Insecurity (2020/21 growing season)

Variable Category	Community Grower	Total
Food Security Level		
Food Secure	0	0/0%
Food Insecure	136	136/100%
Extent of Food Insecurity		
Mild	0	0/0%
Moderate	136	136/100%
Severe	0	0/0%

3.3.1.2 Food availability during the 2020/21 growing season

In terms of food availability: Most of the agri-silviculture community growers (70 often and 66 never) indicated that their food runs out before they get money to buy more. Quite a number of agri-silviculture community growers (94 sometimes and 42 never) cannot afford to eat enough food every day. This situation indicated that the agri-silviculture community growers do not have economic access to grow or purchase food and food does not last until the month end. As a result of the situation, the majority of the agri-silviculture community growers often feels hungry (96 sometimes and 40 always) and their children cannot get enough to eat (40 sometimes and 96 always). According to Maponya et al. (2021), some of the coping strategies agri-silviculture community growers used against food availability includes: getting food on credit from local shops, remittances, social grants, food parcels, food support from neighbours, etc.

3.3.2 Food Security and Food Insecurity Levels during the 2021/22 Growing Season

3.3.2.1 Food accessibility during the 2021/22 growing season

In terms of food accessibility: A total of 126 agri-silviculture community growers indicated that they can now access food as the land allocated and production inputs provided by South Africa Forestry Company Limited (SAFCOL) enabled them to produce food for themselves. Only 10 agri-silviculture community growers indicated that they are still food insecure because of lack of transport money to monitor their land allocation. Similarly, the study conducted by Regassa and Stoecker (2012) indicated that under agroforestry environment, the proportion of severely and moderately food insecure households decreased, whereas the level of mildly food insecure households increased very slightly in the present study compared to the earlier study conducted.

Table 3: Agri-silviculture Community Growers Food Security Levels & Extent of Food Insecurity (2021/22 growing season)

Variable Category	Community Grower	Total
Food Security Level		
Food Secure	126	126/93%
Food Insecure	10	10/7%
Extent of Food Insecurity		
Mild	10	10/7%
Moderate	0	0/0%
Severe	0	0/0%

3.3.2.2 Food availability during the 2021/22 growing season

In terms of food availability: Most agri-silviculture community growers (126 never) indicated that their food does not run out before they get money to buy more. Most agri-silviculture community growers can now buy or have enough food and they are often not hungry (126 never). The children also are now getting enough to eat and agri-silviculture community growers can afford to eat enough everyday (126 always). Very few agri-silviculture community growers (10 always) indicated that they are still food insecure because they did not have transport money to monitor their row allocation at the plantations.

3.3.3 Food Security and Food Insecurity Levels during the 2022/23 Growing Season

3.3.3.1 Food accessibility during the 2022/23 growing season

In terms of food accessibility: All agri-silviculture community growers (136) indicated that they can now access food as the land allocated and production inputs provided by South Africa

Forestry Company Limited (SAFCOL) enabled them to produce food for themselves. Table 4 and Figure 5 indicated that agri-silviculture community growers' food insecurity was flattened year after year and 100% food security achieved at year 3. According to Jiru (2019), improving and strengthening the existing agroforestry practices together with strong integration of livestock, forest production (non-food and food) and crop production would reduce the highly prevailing household food insecurity in the sustainable way.

Table 4: Agri-silviculture Community Growers Food Security Levels & Extent of Food Insecurity (2022/23 growing season)

Variable Category	Community Grower	Total
Food Security Level		
Food Secure	136	136/100%
Food Insecure	0	0/0%
Extent of Food Insecurity		
Mild	0	0/0%
Moderate	0	0/0%
Severe	0	0/0%

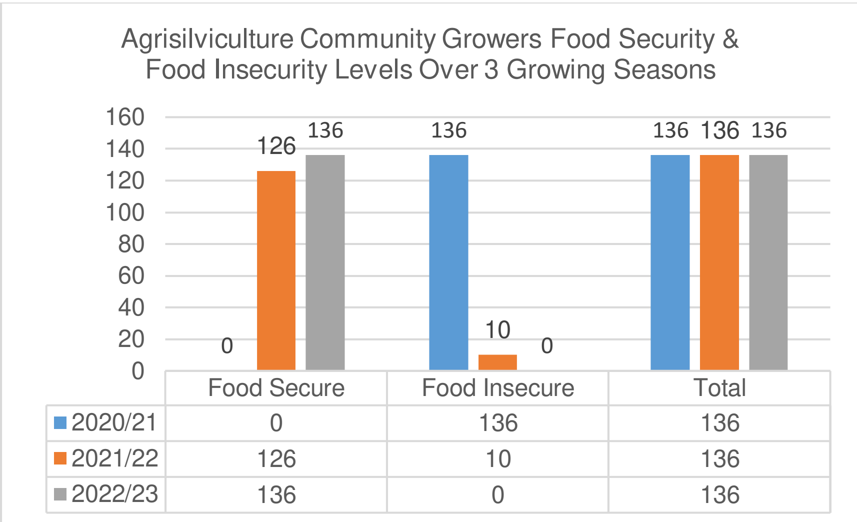


Figure 5: Agri-silviculture Community Growers Food Security and Food Insecurity Levels (3 growing seasons)

3.3.3.2 Food availability during the 2022/23 growing season

In terms of food availability: All agri-silviculture community growers (136 never) indicated that their food does not run out before they get money to buy more. All agri-silviculture community growers can now buy or have enough food and they are often not hungry (136 never). The children also are now getting enough to eat, and agri-silviculture community growers can afford to eat enough everyday (136 always).

3.3.3.3 Food utilisation and diversity during the 2020/21; 2021/22 and 2022/23 seasons

In terms of food diversity, all the agri-silviculture 136 community growers have access to the following food groups: cereals, white tubers and roots, vitamin A rich vegetables, fruit, dark green leafy vegetables, other vegetables, legumes, meat and fish, eggs, dairy, oil and fat, sugar, and spices, condiments and beverages. The Household Dietary Diversity Score (HDDS) reflects the number of different food groups consumed by the community groups. The community growers were asked whether or not any household member consumed a food item pertaining to one of the nine predefined food groups at least once in the last 7 days. This included consumption of the food item at home or home-prepared but consumed outside the home. The nine food groups are: cereals and tubers, vitamin A rich vegetables and fruit, other vegetables and fruit, legumes, meat and fish, eggs, dairy, oil and fat, sugar, and beverages (Labadorios et al., 2009). These food groups should reflect the combination of nutritional needs for a healthy diet. This dietary diversity score can be used to assess changes in diet before and after intervention.

3.4 Agri-silviculture System Energy Element

According to Maponya et al. (2020) small timber growers in Limpopo Province obtained different prices per ton for their timber. The prices obtained were dependent on factors such as the distance to the mill. The highest price per ton was R900 (48USD) per ton (17 small timber growers), while the others were as follows: R300 (16USD) per ton (1 small timber grower); R400 (21USD) per ton (3 small timber growers); R500 (27USD) per ton (9 small timber growers); R600 (32USD) per ton (4 small timber growers); R700 (37.5USD) per ton (6 small timber growers); R750 (40USD) per ton (1 small timber grower); R800 (43USD) per ton (12 small timber growers); and R850 (45USD) per ton (1 small timber grower). The results of the sale of timber indicates that trees are serving as an important source of income. In addition to sale of the wood to mills, communities were using some of the trees to build shelters and kraals (animal enclosures), for medicinal purposes, for fuelwood, etc. Furthermore, the results covered the energy element of the agri-silviculture practice as the rural communities were getting firewood from the plantation for cooking due to lack of electricity. In fact, due to the current electricity load shedding in South Africa, firewood from the plantations is in demand now for the rural communities staying near the plantations.

3.5 Selected Community Growers Market Survey Information

Agri-silviculture community growers had access to informal markets and Figures 6, 7 and 8 are self-explanatory. This is just from the sampled agri-silviculture community growers (136) from the estimated 500 on 70ha. So, the income generated could be higher. As indicated in growing season 2020/21: groundnut sales were R1 055 300 and prices ranged from R750 per 50kg bag to R895 per 50kg bag. In addition, in growing season 2021/22: groundnut sales were R1 313 910 and prices ranged from R850 per 50kg bag to R1000 per 50kg bag. Furthermore, groundnuts sales were R2 343100 and prices ranged from R1000 per 50kg bag to R1400 per 50kg bag. The trend established is that groundnuts quantity increased by +300bags (300*50kg/bag = 15000kg) each growing season. The groundnut prices increased by +R100 each growing season. This information was also confirmed during the informal market survey and through the research team’s observations. It must be emphasised that community growers were reluctant to disclose the exact bags sold to the informal market as they feared that future support will be compromised. So, the research team used triangulation approach which involved questionnaires data collection, monitoring, after harvests tele interviews, follow ups and an informal market survey to augment some of the shortcomings.

The above agroforestry project results are in line with Vrahnakis et al. (2016) who emphasised that agroforestry projects support a variety of rural development resources, thus leading to more stable agribusinesses and rural communities and thus leading to income generation. According to Wilson and Lovell (2016) agroforestry produces a diversity of food and non-food products, providing multiple income streams for the farming households. These products include: timber, crops, fruits, nuts, mushrooms, forages, livestock, biomass, Christmas trees, and herbal medicine (Wilson and Lovell, 2016). Moreover, Wilson and Lovell (2016) stated that “a diverse portfolio of products would allow revenue streams to be spread out over the short-term (crops, forage, livestock, mushrooms, certain fruits like currants), medium-term (nuts, fruits such as apples or persimmons, biomass, medicinal plants), and long-term (lumber, increased property value)”. Furthermore, Xu et al. (2019) emphasised that agroforestry adoption benefit will result in income stability against complete loss of income from monoculture with adverse climatic conditions as loss in market value of one product can be compensated by better prices of other products.

According to Kalaba et al. (2010), in Southern Africa and many developing countries, there is a link between the forest resource and the livelihoods of the rural communities. More than 80% of the rural population in sub-Saharan Africa is poor and traditionally relies on forests for most of their livelihoods including fuelwood and timber as well as other non - timber forest products (Brigham et al., 1996; Schreckenberg et al., 2006; Ngulube, 2000). Fuelwood provides the main source of the total household energy requirements in Southern Africa with the consumption varying from country to country namely: 85% in Mozambique (Brigham et al., 1996), 76% Zambia (Chidumayo, 1997), 91% Tanzania (SADC, 1993) and 14% in South Africa (Gander, 1994). Furthermore, the rural dwellers also generate a wide range of non-timber products which include beeswax, honey, edible fruits, edible insects, wild vegetable, game meat, mushrooms, traditional medicines and fibres (Brigham et al., 1996). For example, Leakey et al. (2005) observed that harvesting of indigenous tree fruits from the wild can boost rural annual income by US 300-US 2000 per household. The use of wild foods such as fruits is observed throughout Southern Africa: Malawi (Akinnifesi et al., 2006), Zambia (Chidumayo and Siwela, 1988), Zimbabwe (Campbell et al. 2002, and South Africa (Shackleton et al., 1998). According to Kalaba et al. (2010) agroforestry practice provides an added benefit as compared to subsistence agriculture by generating cash income from the marketing of diverse products.

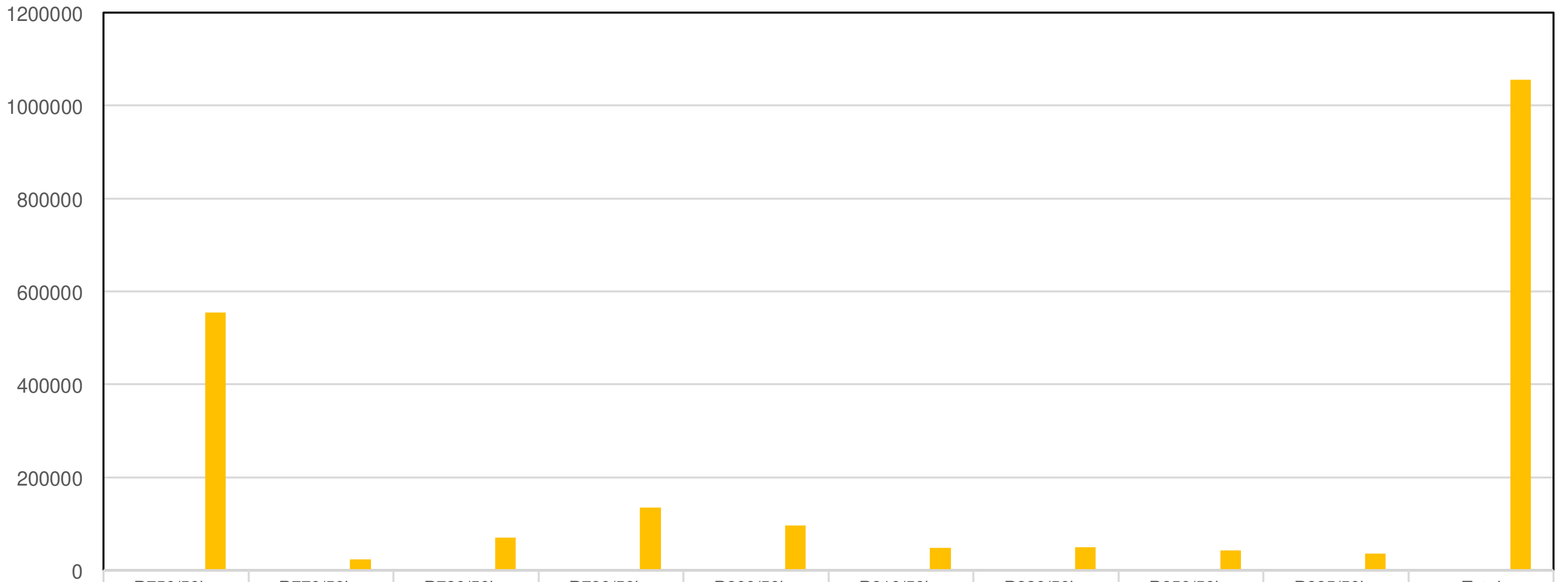
A study conducted in the Limpopo and Mpumalanga Provinces, South Africa by Maponya et al. (2020), addressed the income generation among communities. The study determined the income generation status of the communities before South African Forestry Company Limited (SAFCOL), Department of Environment, Forestry and Fisheries (DEFF) and Mountain To Ocean (MTO) allocated land, provided production inputs and paid stipends and found that income was well generated. It was found that most community growers used the harvest for household consumption while some managed to sell in the informal markets i.e., toll gates, pension pay points, outside towns, within their villages.

The agri-silviculture community growers indicated that some of their challenges include small transport size (5%); lack of transport (80%) and high transport costs (15%), see Figure 9. Hence, they relied on hired transport and processing facility transport. This situation was further emphasised by Tscharntk et al. (2011), who mentioned the development of more coordinated, structured and fair market systems with collective bargaining for both inputs and outputs of agroforestry, better transport infrastructure, involvement of lesser intermediaries in the supply chain, better investment in characterization of tree foods, provision of incentives from payment for eco system services and certification schemes should be adopted. According to Association for Temperate Agroforestry (AFTA) (1997) the diverse nature of agroforestry practices presents marketing challenges. Except for a few products, value chains for agroforestry products are poorly developed. As the added value of agroforestry is relevant to special products, it appears agroforestry added value is unclear to consumers (Hannachi et al., 2017).

Furthermore, Nurrochmat et al. (2021) examined changes in agroforestry management policies in Indonesia by evaluating local development goals, barriers, and risks to agroforestry implementation. Results showed challenges to agroforestry implementation and management being lack of financial resources; inappropriate communication with stakeholders; high costs of transportation; low levels of human capital; and weak coordination. Subsequently, Paudel et al. (2022) found that agroforestry presents opportunities and challenges as a viable way to balance ecological and socio-economic functions in Timor-Leste, where farmers have traditionally implemented agroforestry systems. However, challenges for agroforestry in Timor-Leste still remain, such as lack of knowledge, institutional capacity, and funding.

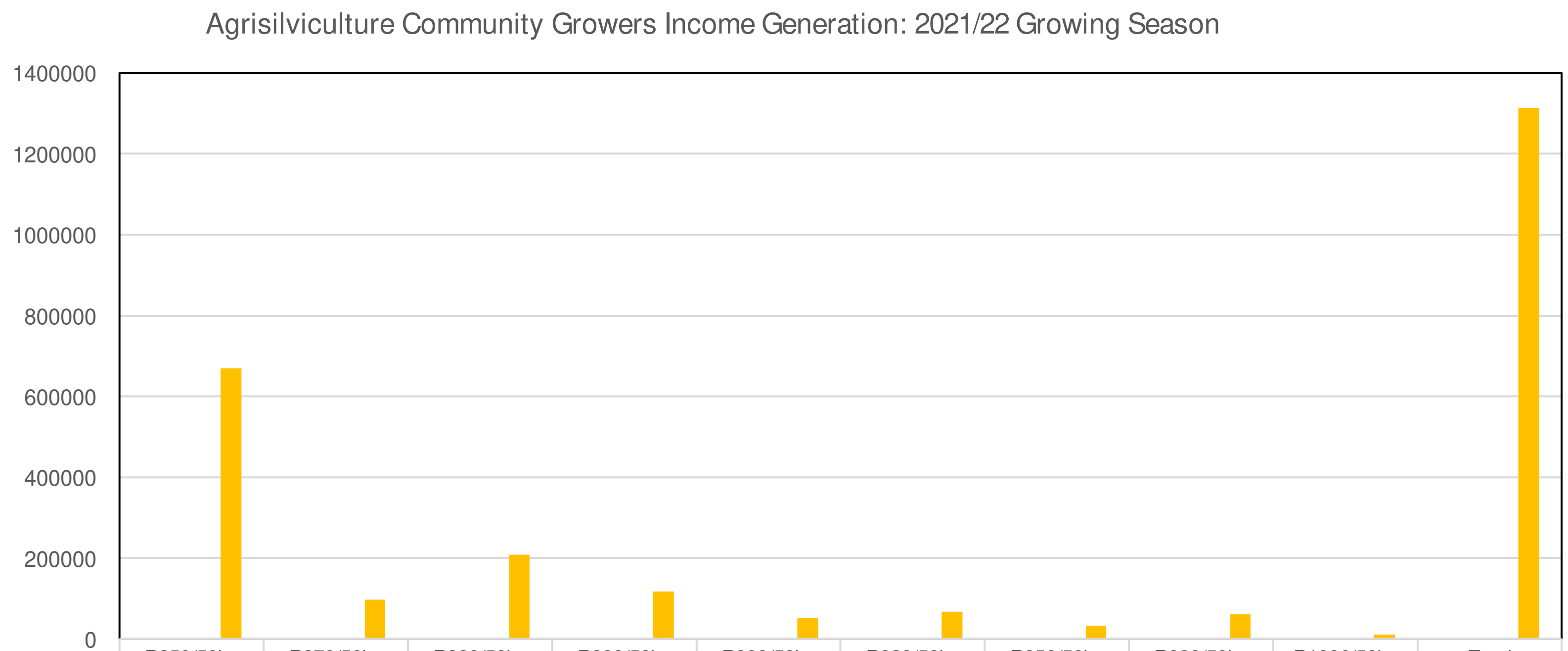
According to Prado et al. (2022) access to credit, an essential component for Brazilian agriculture, is insufficient for family farmers and agroforestry and is instead much more directed to big agriculture and the production of commodities. The structural problems of Brazil's Amazon, such as energy interruptions, poor roads and difficult access to markets — even more problematic when handling delicate fruits in high temperatures make the widespread implementation of agroforestry difficult

Agrisilviculture Community Growers Income Generation: 2020/21 Growing Season



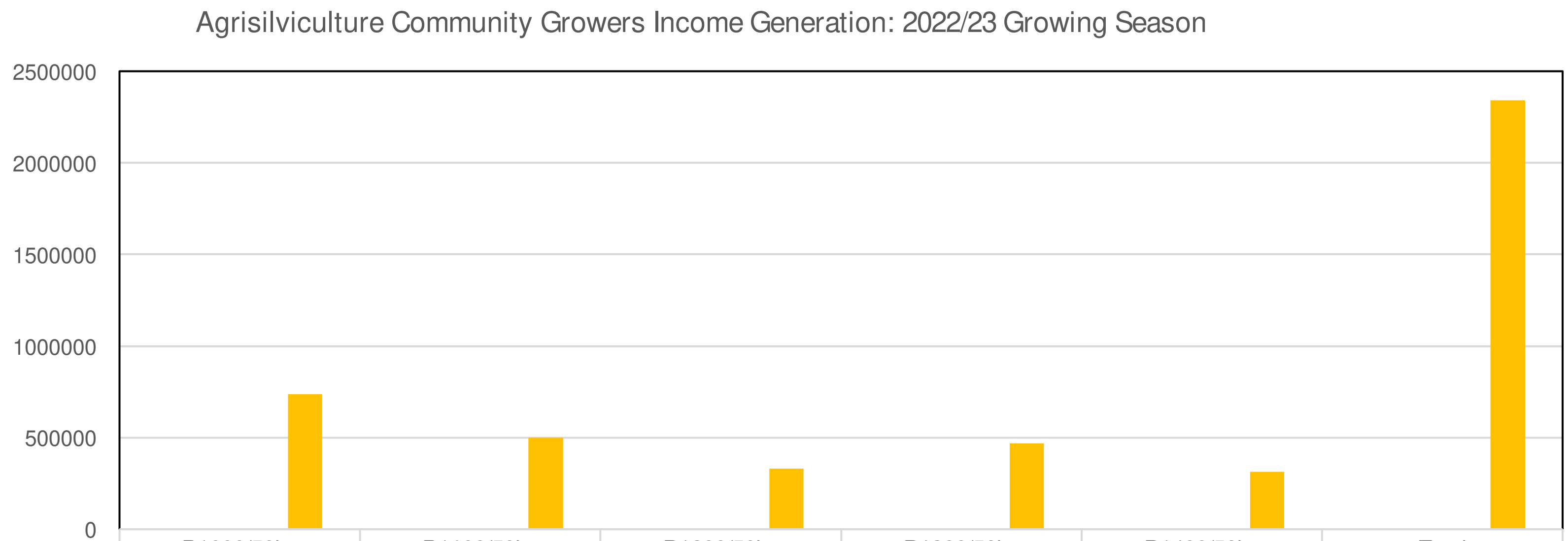
	R750/50kg	R770/50kg	R780/50kg	R790/50kg	R800/50kg	R810/50kg	R830/50kg	R850/50kg	R895/50kg	Total
Community Growers	74	3	9	17	12	6	6	5	4	136
Percentage	54	2	7	14	9	4	4	3	3	100
Bags (50Kg)	740	30	90	170	120	60	60	50	40	1360
Income Gained (Rands)	555000	23100	70200	134300	96000	48600	49800	42500	35800	1055300

Figure 6: Agri-silviculture community growers 2020/21 growing season informal market income gained; 1 United States Dollar = R 18.75.



	R850/50kg	R870/50kg	R880/50kg	R890/50kg	R900/50kg	R920/50kg	R950/50kg	R990/50kg	R1000/50kg	Total
Community Growers	72	11	19	12	5	7	3	6	1	136
Percentage	53	8	15	9	3	5	2	4	1	100
Bags (50Kg)	893	126	266	148	64	83	39	72	12	1703
Income Gained (Rands)	669750	97020	207480	116920	51200	67230	32370	61200	10740	1313910

Figure 7: Agri-silviculture community growers 2021/22 growing season informal market income gained; 1 United States Dollar = R 18.75.



	R1000/50kg	R1100/50kg	R1200/50kg	R1300/50kg	R1400/50kg	Total
Community Growers	40	29	27	25	15	136
Percentage	30	21	20	18	11	100
Bags (50Kg)	736	454	274	359	223	2046
Income Gained (Rands)	736000	499400	328800	466700	312200	2343100

Figure 8: Agri-silviculture community growers 2022/23 growing season informal market income gained; 1 United States Dollar = R 18.75.

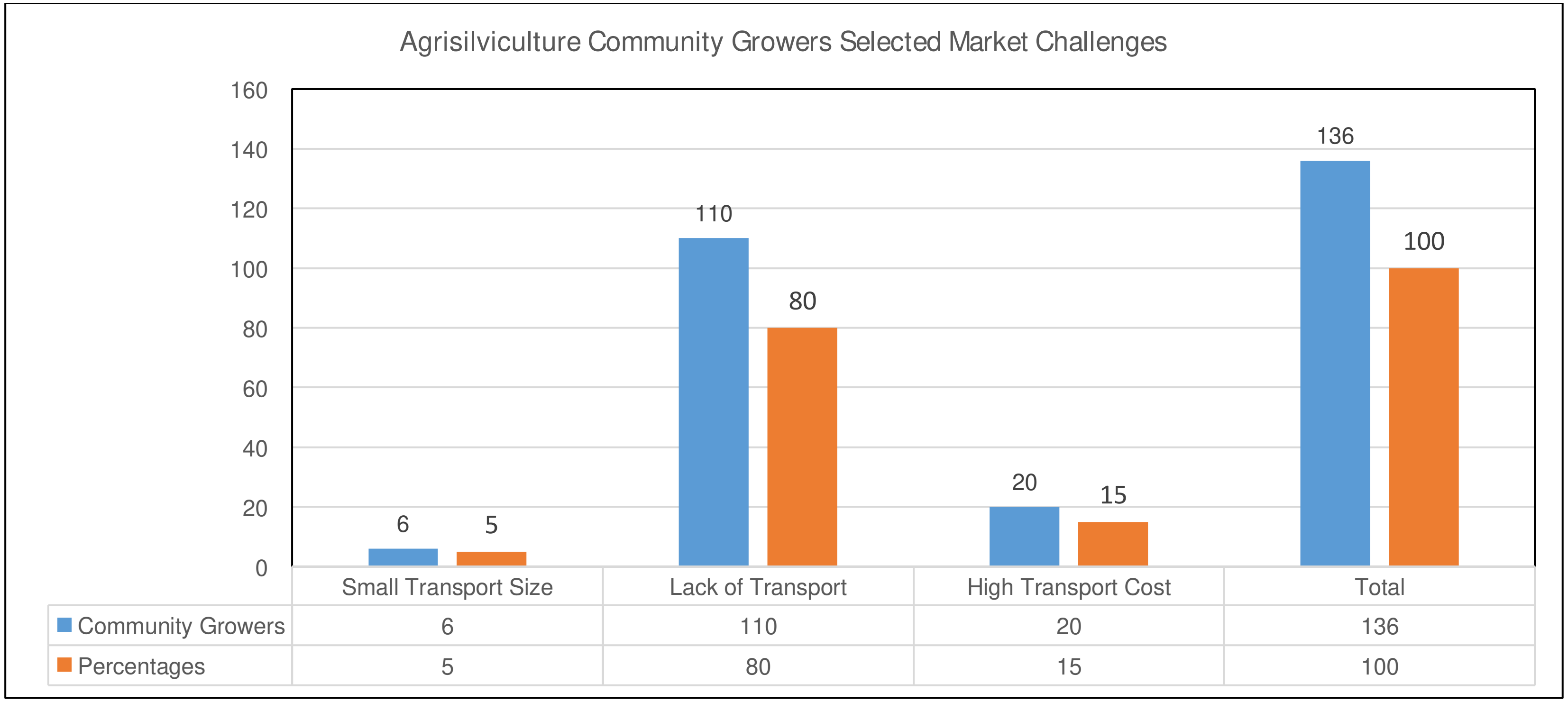


Figure 9: Agri-silviculture community growers selected market challenges

4. CONCLUSION AND RECOMMENDATIONS

The study findings highlighted and concluded that agroforestry can bridge the gap that often separates agriculture and forestry by building integrated systems that address both environmental and socio-economic objectives, income generation, food security and market access. The study indicated that rainfall in the study area is well above agriculture and forestry threshold to sustain commercial forestry activities. Hence, the agroforestry site will allow production of all components (Trees, Crops, Livestock and Pasture). The study further indicated that agri-silviculture community growers' food insecurity was flattened year after year and 100% food security achieved at year 3. Furthermore, the study established an interesting trend where other community growers from other districts are now participating. In addition, another trend established is that groundnuts quantity increases by +300bags (300*50kg/bag = 15000kg) each growing season and groundnuts prices increased by +R100 each growing season. In conclusion, the promotion of agroforestry is important because it offers the prospect of increasing production and hence raising farmer income and food security. Recognizing and tackling the main factors, both socio-economic and biophysical consideration that determine participation of farmers in agroforestry is essential for the adoption of agroforestry. It is, thus, recommended that agroforestry practice should be intensified across all SAFCOL plantations as it is contributing to food security, income generation, market access and sustainable community livelihoods.

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ROLE OF WOMEN IN WATER-FOOD-ENERGY (WFE) NEXUS – CHALLENGES AND OPPORTUNITIES

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ABSTRACT

Water, food, and energy are vital for human existence and development and their interconnectedness plays a significant role in achieving sustainable development goals. Water-Food-Energy (WFE) Nexus represents an approach to examine the complexity and interdependence of the diverse components engaged in managing water, food, and energy. The correlation between water, food, and energy resources and their relationship with environmental, climate change, economic, social, governance, and policy issues necessitates stakeholder collaboration to ensure access to resources, improve efficient management and protection of resources, and provide long-term sustainability. Systematic management of these sectors is essential for attaining Nexus goals and ensuring sustainable development. Despite extensive research on the WFE Nexus in recent years, particularly regarding economic efficiency, sustainable agriculture, and climate change's impact, women's role has often been overlooked. Women contribute significantly to all three water, food, and energy sectors.

Traditionally, women have played vital roles in water management, from gathering and preserving water resources to overseeing household water usage. Their intimate knowledge of local water sources and their nurturing instincts position them as guardians of water in their communities. Women's involvement in water governance can result in improved resource management, enhanced water quality, and increased access to clean water, especially in marginalized and rural areas. Also, women can effectively manage water resources due to having traits such as empathy, sensitivity to the environment, ability to think systemically, and strong communication. One of the women's critical roles in water resources management is identifying and managing water demand, especially for agriculture (food).

Within the WFE Nexus, women play a crucial role in agricultural production, food security, and nutrition. Globally, women comprise a significant portion of the agricultural workforce and are responsible for crop cultivation, livestock rearing, and food processing. Empowering women in agriculture can boost productivity, promote sustainable farming practices, and ensure community food security. Moreover, women's ecological and social knowledge of traditional food systems and their role as caregivers make them advocates for nutritious and culturally appropriate diets. On the other hand, food production and processing of agricultural products also require energy.

In the energy sector, women contribute to the WFE Nexus by promoting sustainable and inclusive energy solutions. As primary users and managers of household energy, women deeply understand energy needs and can drive the adoption of renewable energy technologies at the grassroots level. Their active participation in decision-making processes related to energy planning and policy formulation ensures diverse perspectives and needs are considered, resulting in more effective and equitable energy solutions.

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Promoting gender equality and women's empowerment is crucial for harnessing the full potential of women within the WFE Nexus. Gender-responsive policies and inclusive decision-making processes are essential to ensure women's participation and representation at all levels. Investments in education and skills training can enhance women's capabilities, enabling them to assume leadership roles and contribute to sustainable water, energy, and food management. Empowered women have the agency to drive innovation, promote social equity, and instigate transformative change within the WFE Nexus.

Empowering women and promoting gender equality within the WFE Nexus can lead to more resilient, inclusive, and sustainable outcomes. To fully harness the potential of women, it is crucial to provide them with access to resources, opportunities, and decision-making power that can significantly contribute to establishing the Nexus approach; this will ensure their meaningful participation and leadership in shaping a more sustainable future. Considering the contribution of women as the social capital of countries, this article explores the multifaceted contributions of women in addressing the challenges and opportunities presented by the WFE Nexus, highlighting their roles in enhancing sustainability, equity, resilience, adaptation, better management, and governance.

Keywords : Water-Food-Energy Nexus, Women's Role, Sustainable Development Goals, Women's Empowerment.

1. INTRODUCTION

The interlinkages between water, food, and energy systems have gained increased recognition in recent years under the umbrella concept of the Water-Food-Energy (WFE) Nexus (Mpandeli et al. 2018; Mabhaudhi et al. 2018). This approach aims to understand and optimize the complex connections between managing resources across these three vital sectors. Water, food, and energy support human life, development, and prosperity. Water is required to produce food through agriculture, provide drinking water, and generate energy from hydropower dams and other systems. Agricultural production, in turn, consumes large volumes of water and requires energy for irrigation, processing, and transportation. Energy generation and supply chains depend on reliable water resources for cooling, hydropower, biofuel, and extraction.
The interdependencies and trade-offs between water, food, and energy systems have significant implications for resource security, poverty alleviation, climate change resilience, and socioeconomic development. Rising populations, changing consumption patterns, and environmental stresses are increasing pressure on these intrinsically linked resources; this necessitates integrated, Nexus thinking to optimize resource use across sectors and geographic scales.

The WFE Nexus approach enables stakeholders to identify and leverage synergies while minimizing trade-offs between competing water, food, and energy needs. It promotes coordination between these sectors' institutions, policies, and infrastructure planning. A Nexus perspective is critical to tackling sustainable development goals and ensuring long-term resource security for societies (Simpson and Jewitt, 2019; Biggs et al. 2015). However, its successful implementation requires the participation of diverse stakeholders, including frequently underrepresented groups such as women (Khadka, 2022; Sani and Scholz, 2022; Hlahla, 2022).

Women contribute significantly to all three water, food, and energy sectors (Hlahla, 2022; Tantoh et al. 2021; Njie and Ndiaye, 2013). Traditionally, women have played vital roles in water management, from gathering and preserving water resources to overseeing household water usage. Their intimate knowledge of local water sources and their nurturing instincts position them as guardians of water in their communities. Women's involvement in water governance can result in improved resource management, enhanced water quality, and increased access to clean water, especially in marginalized and rural areas (Mommen et al. 2017; Witinok-Huber et al. 2018). Also, women can effectively manage water resources due to having traits such as empathy, sensitivity to the environment, ability to think systemically, and strong communication.

Women's participation in the WFE Nexus is crucial in agricultural production, food security, and nutrition (Satyavathi et al. 2017). Globally, women comprise a significant portion of the agricultural workforce and are responsible for crop cultivation, livestock rearing, and food processing (Ayodele, 2009). Empowering women in agriculture can boost productivity, promote sustainable farming practices, and ensure community food security. Moreover, women's ecological and social knowledge of traditional food systems and their role as caregivers make them advocates for nutritious and culturally appropriate diets (Singh et al. 2020).

In the energy sector, women contribute to the WFE Nexus by promoting sustainable and inclusive energy solutions (Pearl-Martinez and Stephens, 2016). As primary users and managers of household energy, women deeply understand energy needs and can drive the adoption of renewable energy technologies at the grassroots level (Elnakat and Gomez, 2015; Shrestha et al. 2021). Active participation of women in decision-making processes related to energy planning and policy formulation ensures that we consider diverse perspectives and needs, resulting in more effective and equitable energy solutions.

Access to water, food, and energy are fundamental human rights. The WFE Nexus describes the interdependency between these three core resources. The Nexus approach recognizes that sustainability challenges are interconnected—decisions in one sector affect the availability and affordability of resources in others (Mohtar and Daher, 2012). By 2050, as the world's population is estimated to reach 9.7 billion, projections indicate that demand across the WFE Nexus will increase by 30-50% (WWAP, 2014). Climate change is exacerbating resource constraints. Governments and institutions worldwide are grappling with equitably and sustainably managing the WFE Nexus to support social, economic, and environmental objectives.

While the WFE Nexus has gained traction as an approach to improving resource management and sustainability, research has yet to examine the multifaceted contribution. This article aims to highlight women's important yet often overlooked roles within the WFE Nexus.

2. THE CRITICAL ROLE OF WOMEN IN THE WFE NEXUS

Women's vital yet often overlooked roles in water management encompass collecting, using, and managing water resources, especially in rural and marginalized settings (Naiga et al. 2017; Figueiredo and Perkins, 2013). They bear the strenuous task of fetching water from distant or unsafe sources in many developing countries, fostering their deep understanding of water conservation. Additionally, women oversee household water use, sanitation, and hygiene, efficiently budgeting water supplies (UNICEF and WHO, 2023). Culturally, they serve as stewards, preserving local water resources and addressing issues like pollution or scarcity (Caretta, 2020). Evidence demonstrates that involving women in water committees and decision-making roles enhances resource management, sustainability, access, and water quality and has ripple effects on health, education, income, and local capacity building (Mommen et al. 2017). Women's innovative problem-solving abilities contribute to holistic solutions, making their inclusion crucial for equitable and sustainable water management.

Women's participation in decision-making and managing water resources has been shown to impact water governance and sustainability positively. According to a report from the World Bank, women, on average, make up 18% of the total workforce in water-related organizations, with women engineers and managers accounting for 23% of this share (World Bank, 2019). In Armenia and Ukraine, women's civil society contributions to developing and implementing the Protocol on Water and Health have made a difference (Bouman, 2017). In South Africa, women's roles in integrated water resource management have been underestimated, and they face various challenges that hinder them from effectively performing their decision-making roles (Elias, 2015). In Kenya, community participation in forest and water management planning is essential for resource management planning at the local level, and the integration of community participants from both spheres into both forest and water management planning is recommended (Ombogoh et al. 2022). In India and Nepal, women outdo men in terms of their involvement in the use and management of water resources. However, they face categorical exclusion and denial of equal sharing of benefits from natural resources (Upadhyay, 2005). These studies highlight the importance of women's participation in water governance and the need for gender-sensitive approaches to water provision and management processes.

Women also play a crucial role in the Food component of the WFE Nexus. They are essential in local and national food systems, contributing significantly to food production, processing, distribution, and consumption (Malapit et al. 2020; Bhandari, 2017). Women's participation in agricultural cooperatives, self-help groups, and community-based organizations strengthens social cohesion and collective action for sustainable agriculture.

The results of conducted studies indicate that at the household level, women's participation and management lead to an increase in farm management skills and, consequently, result in better food security (Wei et al. 2021; Sharaunga et al. 2016; Essilfie et al. 2020). Recent studies conducted in 707 maize farms in Kenya show that empowering women has a direct impact on increasing maize production efficiency. This study has shown that farms managed by men and women have higher productivity than farms managed solely by men or women. This finding suggests that women's involvement in agriculture can improve farm productivity and, as a result, improve food security and poverty reduction (Diiro et al. 2018).

On the other hand, optimal water and food management can lead to efficient energy utilization since these resources are closely interconnected and interdependent. For example, effective water management can reduce the amount of water used in food production, reducing the energy required for pumping, purification, and water transportation (Elshorbagy, 2021). Effective food management can reduce food waste, reducing the energy needed to produce, transport, and dispose of food (Seferlis and Voutetakis, 2008). Efficient water and food management can lead to more sustainable and efficient use of energy resources, which is crucial for addressing resource scarcity and climate change challenges.

Social and cultural barriers limit women's decision-making power and capacity to own, inherit, or benefit from land, water sources, agricultural inputs, food distribution, and energy technologies (FAO, IFAD & WFP, 2018). Women face constraints accessing information, training, financing, markets, and policy negotiations related to WFE systems (UN Women, 2017). These exclusions impede women's productivity and innovation in efficiently managing WFE resources.

Women are disproportionately vulnerable to the impacts of resource degradation and scarcities across WFE systems. Time-consuming responsibilities for collecting water and fuelwood fall predominantly on women and girls, with significant health consequences (UNDP, 2006). Climate change-induced droughts, floods, and erratic rainfall undermine food security and escalate burdens on women farmers (Alston, 2014). Described as *time poverty*, the cumulative impacts of gendered roles and barriers to managing WFE resources significantly disadvantage women and girls (FAO, IFAD, & WFP, 2018).

In contrast, research shows that enhancing gender equality and women's leadership in governing WFE resources improves sustainability and equality outcomes. A meta-analysis covering over 500 villages in India found that water committees with female presidents spent 66% more on system maintenance (Agarwal, 2009). In Nepali forestry groups, more significant proportions of women in executive committees correlated with improved forest conditions (Agarwal, 2009). Evidence from Kenya, Malawi, and Sudan demonstrates that women farmers reinvest significantly more profits in food, health, and education than men, reducing poverty (FAO, 2011).

By overlooking gender dynamics, traditional top-down resource governance often fails to capture women's unique knowledge, priorities, and needs (Leach et al. 2015). Excluding women's perspectives results in technocratic approaches undermining long-term sustainability and gender equity (FAO, IFAD, & WFP, 2018). Instead, research underscores the importance of grassroots women's empowerment coupled with high-level gender mainstreaming across institutions (Raman, 2017).

3. GENDER EQUALITY IN THE WFE NEXUS

The WFE Nexus is a critical concept emphasizing the interdependence of water, food, and energy resources. It highlights the need for integrated management and policy-making to ensure the sustainable use of these resources. Women play a significant role in this Nexus, as they are often responsible for managing water, food, and energy resources at the household and community levels.

Women are often the primary water, food, and energy managers in households and communities, particularly in developing countries (Oparaocha and Dutta, 2011). They collect water, prepare food, and manage household energy needs. As a result, women have unique knowledge and experience in managing these resources, which can contribute to more sustainable and efficient use of water, food, and energy.

Moreover, women's participation in decision-making processes related to the WFE Nexus can lead to more equitable and sustainable outcomes. For example, involving women in water management can result in improved water conservation and allocation and better household access to clean water (Mommen et al. 2017). Similarly, empowering women in the agricultural sector can increase food production and improve food security, as women often have valuable knowledge about local crops and farming practices (Murugani and Thamaga-Chitja, 2019).

4. WOMEN'S EMPOWERMENT STRATEGIES IN THE WATER, FOOD, AND ENERGY SECTORS

Women's empowerment is imperative to enhance the effective management of the WFE Nexus. Empowerment involves furnishing women with opportunities and resources to facilitate equitable engagement in all dimensions of overseeing the water, food, and energy Nexus. Women's empowerment denotes their active participation in decision-making processes pertaining to managing water, food, and energy resources, encompassing the realization of economic and social advantages from these resources. Moreover, when qualified, it entails their assumption of leadership and decision-making roles within these domains. Here are some strategies aimed at empowering women within this context:

i. Education and Training: Equipping women with education and training in water, food, and energy management can augment their knowledge and proficiency in these domains; this encompasses the acquisition of technical expertise, an understanding of marketing strategies, and the cultivation of entrepreneurial skills (Mubeen et al. 2022).

ii. Promoting Women's Participation in Decision-Making: Encouraging women to embrace leadership positions within organizations linked to the WFE Nexus can substantiate incorporating their perspectives and requirements into decision-making procedures (Kevany and Huisingh, 2013).

iii. Addressing Cultural Barriers: Confronting cultural norms and stereotypes that restrict women's access to leadership roles assumes paramount significance in attaining gender parity and empowering women in the governance of the WFE Nexus (Galsanjigmed and Sekiguchi, 2023; Jayachandran, 2020).

iv. Land Tenure and Resource Access: Ensuring secure land tenure and unfettered access to resources is pivotal in enabling women to actively manage water, food, and energy systems (Jemase and Chesikaw, 2021).

v. Support from NGOs and Government Policies: Non-governmental organizations (NGOs) greatly influence training and empowering women to swiftly establish livelihoods through enterprise creation and entrepreneurship within the WFE Nexus (Gupta, 2021). Governments should refine extant policies and offer women equal opportunities within these sectors.

vi. Networking and Collaboration: Encouraging women to forge networks and collaborate with other stakeholders within the WFE Nexus can facilitate their access to resources, dissemination of knowledge, and formation of partnerships for more efficacious management (Abdullah et al. 2021).

Implementing these strategies empowers women to contribute more effectively to managing the WFE Nexus, culminating in more sustainable and equitable outcomes for all stakeholders involved.

5. THE BENEFITS OF EMPOWERING WOMEN IN WATER-FOOD-ENERGY SECTORS

Empowering women in the WFE Nexus can have significant social, economic, and environmental benefits. From a social perspective, women's empowerment can stimulate the heightened involvement of women in decision-making processes concerning the administration of water, food, and energy resources. This, in turn, can yield a range of positive outcomes, including greater gender equality, heightened awareness of water, food, and energy challenges, and enhanced decision-making capabilities. Economically, women's empowerment can usher in increased economic prospects for women, resulting in augmented incomes, reduced poverty levels, and ameliorated household livelihoods. On the environmental front, women's empowerment can usher in heightened sustainability in managing water, food, and energy resources. Women have traditionally borne responsibility for overseeing these resources within households and communities. Empowering women can catalyze the development of more sustainable approaches to resource management, contributing to the long-term ecological viability of these critical domains. Some of these benefits include:

i. Improved resource management: Women's involvement in decision-making can lead to more efficient and sustainable use of water, food, and energy resources, as they often have unique knowledge and experience in managing these resources (Figueiredo and Perkins, 2013).

ii. Increased food security: Empowering women in agriculture can increase food production and improve food security, as women often have valuable knowledge about local crops and farming practices.

iii. Enhanced economic opportunities: Empowering women in the WFE Nexus can create new economic opportunities for women, such as jobs in the renewable energy sector or leadership positions in water and food management organizations (Colantonio and Pennell a, 2022).

iv. Reduced gender inequality: Addressing gender inequalities in the WFE Nexus can contribute to broader gender equality goals, as women's empowerment in this context can challenge traditional gender roles and promote more equitable power dynamics (Arnot and Swartz, 2018).

v. Improved health outcomes: Access to clean water, nutritious food, and reliable energy sources can have significant positive impacts on women's health, as well as the health of their families and communities (Rahman and Alam, 2021).

6. CHALLENGES OF WOMEN'S EMPOWERMENT AND PRESENCE IN WFE NEXUS MANAGEMENT

The results of a project conducted by the Global Water Partnership - Mediterranean (GWP-MED) in the MENA (Middle East and North Africa) region, comprising Egypt, Jordan, Lebanon, Morocco, and Palestine, have shown that several significant factors hinder women's involvement in decision-making in the water sector. These factors include a male-dominant society, a male-female quota imbalance, a lack of supportive frameworks, negative perceptions, and a shortage of female expertise (Afailal et al. 2021). Based on the review of various studies, the most critical challenges to increasing women's participation in managing water, food, and energy resources include:

i. Gender norms and cultural barriers: Traditional gender roles often assign women responsible for managing household resources, including water and energy. However, these roles may limit women's participation in decision-making processes related to water, food, and energy management at the community level (Tantoh et al. 2021; Yahaya et al. 2007).

ii. Access to education and resources: Women in many regions need more access to education, credit, income, and extension services, which can hinder their ability to participate in WFE Nexus management effectively (Ravula et al. 2020; Yahaya et al. 2007).

iii. Time constraints: Women often have multiple responsibilities, including household chores, childcare, and agricultural work. These time constraints can limit their ability to engage in WFE Nexus management activities (Suhardiman et al. 2023).

iv. Representation in decision-making bodies: Despite official quotas aimed at promoting women's participation in organizations like Water Users Associations (WUAs), some women may choose not to actively engage with these organizations due to cultural norms, workload or a lack of perceived benefits (Suhardiman et al. 2023).

v. Limited knowledge and skills: Women may need more knowledge and skills to effectively participate in WFE Nexus management, particularly in areas where they have not traditionally been involved (Villamor et al. 2018; Yahaya et al. 2007).

vi. Migration-induced challenges: Large-scale male outmigration can place new pressures on women, especially regarding labor division in farm households and involvement in WUAs; this can lead women to take on additional responsibilities and face new challenges in managing water, food, and energy resources (Scogin, 2023).

To address these challenges, promoting gender equality, providing women access to education and resources, and encouraging active participation in decision-making processes related to WFE Nexus management are essential. Additionally, recognizing and addressing the unique challenges women face due to migration and other factors can help ensure their effective participation in managing these critical resources.

7. ROLE OF WOMEN PARTICIPATION IN APPLICATION OF WFE NEXUS IN MENA REGION

The Middle East and North Africa (MENA) region, which includes Iran, Iraq, Algeria, Egypt, Bahrain, Israel, Kuwait, Libya, Jordan, Morocco, the United Arab Emirates, Lebanon, Saudi Arabia, Oman, Yemen, Qatar, Tunisia, and Syria, is one of the driest regions in the world. Water consumption is increasing in various sectors, including agriculture, industry, and domestic in the region, while climate change and reduced rainfall have also negatively impacted the region's water resources. The region faces unique challenges in the three areas of water, food, and energy due to the limited availability of water, heavy reliance on desalination, extensive use of groundwater, and high energy needs (Sowers et al. 2017).
These challenges significantly impact the region's water resource management, food production, and energy production. Therefore, it is essential to pay attention to the WFE Nexus in the MENA region to manage water and energy scarcity, ensure food security, and avoid security tensions. The application of the WFE Nexus in the Middle East and North Africa (MENA) region has been investigated in a comprehensive study (Maftouh et al. 2022). Agriculture is the main water consumer in many countries in this region, and reducing water consumption in the agricultural sector can lead to significant savings. Therefore, recycling and reusing agricultural drainage can lead to significant savings in water abstraction, leading to better WFE nexus management in this region. Water is also heavily consumed to extract and refine fossil and biofuels. In addition, significant energy is expended for pumping groundwater and desalination processes in the region. Increasing water and energy efficiency in the agricultural sector through innovative technologies can considerably improve the management of water, food, and energy resources in this region. Therefore, changing consumption patterns and reducing food waste in this region is also very important.

The case study conducted by Maftouh et al. (2022) revealed that the water, food, and energy sectors have a strong interconnection in this region. Groundwater pumping accounts for a significant portion of electricity consumption, highlighting the necessity for improved water resource management to enhance efficiency and prevent water and energy wastage. Furthermore, considering the conditions of countries in this region, Maftouh et al. (2022) concluded that although the capacity for deploying renewable energy systems such as solar and wind energy is high, the majority of energy supply comes from fossil fuels, and the role of renewable energies in these countries is minimal. Therefore, this region has ample opportunities to increase the efficiency of water, food, and energy resources.

Developing women's capacity and empowerment in managing water, food, and energy resources can address some of the significant challenges related to the WFE Nexus in the MENA region. Women produce over 50% of agricultural food globally and are responsible for 60 to 80% of food production in most developing countries, including MENA countries (Kabeer et al. 2019; World Bank, 2023). Further, according to a study by Maier et al. (2022), women's representation in the energy sector in the MENA region is only between 7 and 9%, while the global average is 32%. By raising women's awareness of environmental and water resource issues, they can play a more significant role in sustainable water resource management. Furthermore, women's involvement in decision-making related to water resources can lead to the formulation of more effective policies and programs for water conservation and improved water resource utilization.

Figure 1 outlines the broad areas in which women can be instrumental in each segment of the WFE Nexus. Table 1 summarizes some of the benefits of women's participation in addressing various challenges facing the WFE Nexus in the MENA region.

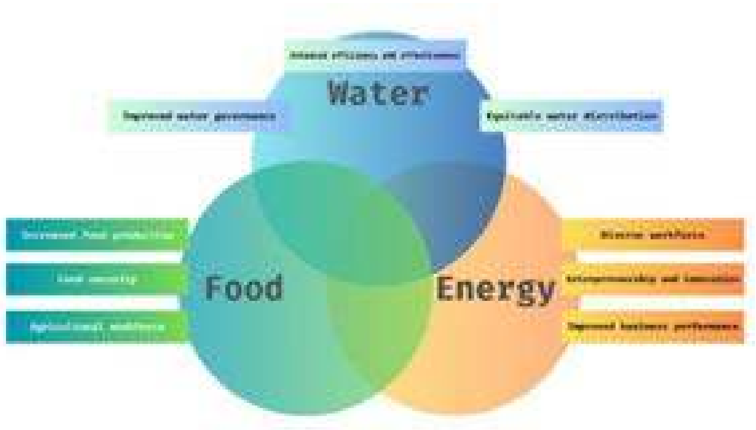

Figure 1. Some of the benefits of women's participation in each sector of the WFE Nexus

Table 1: Benefits of women's participation in addressing various challenges in the WFE Nexus in the MENA Region

Num.	Subject	Challenge	Role of women in addressing the challenge
1	Water Scarcity	Severe water resource scarcity in many regional countries	Women can play a crucial role in reducing water consumption by promoting water-efficient household practices. They possess significant inherent knowledge about water resources and, through increasing their awareness and competence in water management, can contribute to ameliorating water scarcity.
2	Increasing Demand	Escalating water consumption across various sectors	Educating women as primary household resource managers can lead to the modification of consumption patterns. As half of society's population and influential actors in families and communities, they can substantially contribute to water management through prudent water usage and disseminating this culture.
3	Unregulated Water Extraction	Unregulated groundwater depletion	Women's participation in decision-making and policymaking can result in more sustainable solutions.
4	Low Water Efficiency in Agriculture	Excessive water dependency and wastage in agriculture	Women in agriculture can contribute to reducing water dependence and excessive waste in the agricultural sector by employing innovative and more efficient irrigation and water management techniques.
5	Desalination	High energy costs for desalination-driven water supply	Collaboration and utilizing women's specialized knowledge can lead to developing new and environmentally friendly methods for securing water resources.
6	Wastewater and Pollution	Pollution of water resources due to wastewater and discharges	Raising awareness among women about wastewater management is highly effective in preventing resource pollution.
7	Renewable Energy	Underutilization of renewable energy capacities	Women can play a central role in promoting the use of renewable energy at the household and community levels.
8	Integrated Water Resource Management	Lack of integrated water and energy resource management	Considering women's perspectives and participation as half of a society's population is essential for achieving integrated water and energy resource management.
9	Climate Change and Drought	High vulnerability to climate change and drought events	As the primary family caregivers, women should receive the necessary training to cope with extreme events and play an effective role in increasing resilience and adaptability to such events.
10	Planning	Inadequate data and information for optimal planning	Women's collaboration and participation in data recording and collection, as well as leveraging their specialized research expertise, contribute to more comprehensive data and information needed to manage and plan water, food, and energy resources.

8. CONCLUSION

The role of women in the WFE Nexus is crucial for achieving sustainable development goals and ensuring long-term resource security. Despite extensive research on the WFE Nexus, researchers have often overlooked women's contributions. However, women play significant roles in all three sectors - water, food, and energy.

In water management, women traditionally gather and preserve water resources and oversee household water usage. Their intimate knowledge of local water sources and nurturing instincts make them guardians of water in their communities. Women's involvement in water governance can lead to improved resource management, enhanced water quality, and increased access to clean water, especially in marginalized and rural areas.

Within the WFE Nexus, women also play a crucial role in agricultural production, food security, and nutrition. They comprise a significant portion of the agricultural workforce globally and are responsible for crop cultivation, livestock rearing, and food processing. Empowering women in agriculture can boost productivity, promote sustainable farming practices, and ensure community food security. Additionally, women's ecological and social knowledge of traditional food systems and their role as caregivers make them advocates for nutritious and culturally appropriate diets.

In the energy sector, women contribute to the WFE Nexus by promoting sustainable and inclusive energy solutions. As primary users and managers of household energy, women deeply understand energy needs and can drive the adoption of renewable energy technologies at the grassroots level. Active participation of women in decision-making processes related to energy planning and policy formulation ensures that it considers diverse perspectives and needs, resulting in more effective and equitable energy solutions.

To fully harness the potential of women within the WFE Nexus, it is crucial to promote gender equality and women's empowerment. Gender-responsive policies and inclusive decision-making processes are essential to ensure women's participation and representation at all levels. Investments in education and skills training can enhance women's capabilities, enabling them to assume leadership roles and contribute to sustainable water, energy, and food management. Empowered women have the agency to drive innovation, promote social equity, and instigate transformative change within the WFE Nexus.

By providing women with access to resources, opportunities, and decision-making power, we can significantly contribute to establishing the Nexus approach and ensure their meaningful participation and leadership in shaping a more sustainable future. Empowering women and promoting gender equality within the WFE Nexus can lead to more resilient, inclusive, and sustainable outcomes for all.

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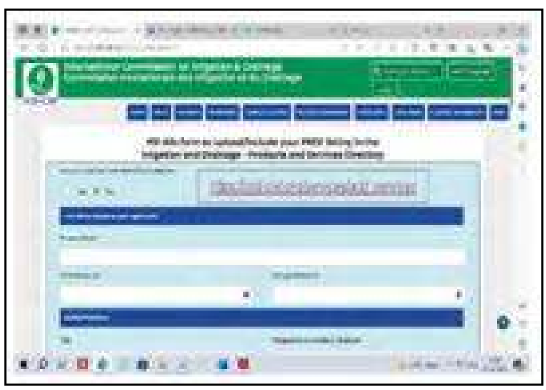

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Question 64: What alternative water resources could be tapped for irrigated agriculture?

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Question 65: Which on-farm techniques can increase water productivity?

Quelles techniques agricoles peuvent augmenter la productivité de l'eau?

ISBN 978-81-89610-36-4

9 788189 610364 >

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Hosted by:

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