frontiers | Frontiers in Sustainable Food Systems

TYPE Perspective
PUBLISHED 29 August 2023
DOI 10.3389/fsufs.2023.1207197

OPEN ACCESS

EDITED BY
Sudhir Yadav,
University of Queensland, Australia

REVIEWED BY
John Dixon,
The University of Queensland, Australia

*CORRESPONDENCE
Andrianto Ansari
andrianto.ansari@mail.ugm.ac.id

RECEIVED 18 April 2023
ACCEPTED 08 August 2023
PUBLISHED 29 August 2023

CITATION
Ansari A, Wuryandani S, Pranesti A, Telaumbanua M, Ngadisih, Hardiansyah MY, Alam T, Supriyanta, Martini T and Taryono (2023) Optimizing water-energy-food nexus: achieving economic prosperity and environmental sustainability in agriculture. *Front. Sustain. Food Syst.* 7:1207197. doi: 10.3389/fsufs.2023.1207197

Optimizing water-energy-food nexus: achieving economic prosperity and environmental sustainability in agriculture

Andrianto Ansari[1]*, Shafira Wuryandani[2], Arin Pranesti[3], Mareli Telaumbanua[4], Ngadisih[5], Muhammad Yusril Hardiansyah[6], Taufan Alam[1], Supriyanta[1], Tri Martini[7] and Taryono[1,8]

[1]Department of Agronomy, Faculty of Agriculture, Universitas Gadjah Mada, Yogyakarta, Indonesia, [2]Department of Bioenvironmental Systems Engineering, National Taiwan University, Taipei, Taiwan, [3]Department of Accounting, Faculty of Economics and Business, Universitas Negeri Yogyakarta, Yogyakarta, Indonesia, [4]Department of Agricultural Engineering, Faculty of Agriculture, Lampung University, Bandar Lampung, Indonesia, [5]Department of Agricultural and Biosystems Engineering, Faculty of Agricultural and Technology, Universitas Gadjah Mada, Yogyakarta, Indonesia, [6]Department of Global Agriculture Technology and Genomic Science, National Taiwan University, Taipei, Taiwan, [7]Research Center for Sustainable Production System and Life Cycle Assessment, National Research and Innovation Agency of the Republic of Indonesia, South Tangerang, Indonesia, [8]Agrotechnology Innovation Center, Universitas Gadjah Mada, Yogyakarta, Indonesia

The increasing global population, rapid urbanization, and climate change are putting unprecedented pressure on limited water and energy resources for food production. It requires integrated management of the key resources to achieve economic and environmental sustainability. The water-energy-food (WEF) nexus, in conjunction with circular bioeconomy (CBE) principles, offer a promising approach to achieve sustainable agriculture. It provides the integration between interconnectedness and interdependencies of the resources through closing bio-resource loops. Using bio-based materials, renewable energy resources, and implementing energy-efficient practices and technologies can maximize synergistic among the resources and promote sustainable agriculture while minimizing negative environmental impacts. However, there are challenges and limitations, such as economic conditions, proper infrastructure and technology, policy and governance support, public awareness, and potential trade-offs and conflicts. Moreover, it also faces various social and cultural challenges in implementing this approach. Therefore, to overcome these challenges and limitations, the need for innovative and sustainable technologies, significant investments in research and development, infrastructure and training, environmental campaign, innovative financing mechanisms and policies that incentivize sustainable practices, and support from stakeholders and the public are essential.

KEYWORDS
circular bioeconomy, water, energy, food, environment, nexus

1. Introduction

Agriculture, as a major consumer of water and energy resources, significantly impacts the environment through land use change, greenhouse gas emissions, and biodiversity loss (Lynch et al., 2021). With the global population surpassing 8 billion people, the limited resources for food production, coupled with the need for food security, pose unprecedented pressure on water and energy supplies (Li et al., 2021). This necessitates integration and a holistic perspective to achieve sustainable outcomes and balance the food supply and demand. The water-energy-food (WEF) nexus approach has gained global attention and led to international and regional agreements emphasizing the interconnectedness and interdependence of these critical elements (Geressu et al., 2020; Yue and Guo, 2021). It highlights three critical elements for ensuring food security, reducing poverty, improving human health, and protecting the environment, and those effective solutions must be based on a thorough understanding of the interdependencies and feedback between these systems (Geressu et al., 2020; Siderius et al., 2022). This concept also recognizes that these elements are not separate entities but are profoundly interconnected, and those changes in one element can significantly impact the others.

The nexus approach, encompassing resource systems, resource management, and drivers of change, can be strengthened by integrating circular economy (CE) considerations, particularly in the context of the bioeconomy (BE), which utilizes biological resources and processes to produce goods, services, and energy sustainably, aligning with the principles of circularity (Hetemäki et al., 2017; Braun et al., 2022). Within the bioeconomy framework, the term "circular bioeconomy" has emerged to describe an economic system that combines CE principles with utilizing biological resources. The circular bioeconomy (CBE)—manifesting the intersection between CE and BE— aspires to create a sustainable and regenerative system that maximizes the value derived from biological resources, such as biomass and organic waste, as inputs, while minimizing waste and negative environmental impacts within a closed-loop system (Tan and Lamers, 2021; Kumar Sarangi et al., 2023). While the CE is a broader concept that encompasses all sectors and resources, the CBE narrows its focus to the sustainable utilization of biological resources and processes to achieve circularity and sustainability.

The WEF nexus and CBE are interconnected concepts that address the sustainable management of resources (Biggs et al., 2015; Tan and Lamers, 2021; Peña-Torres et al., 2022). The WEF nexus recognizes the interdependencies and trade-offs between water, energy, food, and ecosystems (Wu et al., 2021; Yue and Guo, 2021). It emphasizes the need for an integrated approach to manage these resources, considering their interconnectedness and the potential impacts of decisions made in one sector on others. The CBE, on the other hand, focuses on utilizing bio-based resources and processes in a sustainable and regenerative manner (Stegmann et al., 2020; Tan and Lamers, 2021). It aims to replace the linear take-make-dispose model with a circular approach that maximizes resource efficiency, reduces waste, and minimizes adverse environmental impacts. The CBE can contribute to the goals of the WEF nexus by promoting resource efficiency and reducing the strain on water, energy, and food systems (Tan and Lamers, 2021; Peña-Torres et al., 2022). This concept revolutionizes the traditional economic principle that solely emphasizes extraction, production, and disposal, which is inherently unsustainable in the long term. This transformative concept decouples economic growth from resource depletion and environmental degradation, fostering a more sustainable and resilient future for current and future generations (Stegmann et al., 2020; Khan et al., 2021).

By adopting circular practices in the bioeconomy within WEF, such as the utilization of renewable biomass, organic waste, and byproducts, significant benefits can be achieved regarding resource efficiency, economic prosperity, and environmental sustainability. These practices minimize the need for excessive resource inputs, decrease waste generation, and mitigate environmental pollution. In turn, the principles of the WEF nexus can guide decision-making within the CBE by considering the impacts and trade-offs among water, energy, food, and ecosystems; it helps ensure that the CBE's practices align with broader sustainability objectives, such as water and energy conservation, food security, and ecosystem preservation (Stegmann et al., 2020; Tan and Lamers, 2021; Yue and Guo, 2021). Therefore, this perspective aims to explore the potential of synergies between the WEF nexus approach with CBE principles, with the overarching goal of fostering economic prosperity and environmental sustainability in agriculture. Ultimately, the goal of this perspective is to contribute to a more sustainable and resilient agricultural system that can meet the population's food, energy, and water needs while protecting the environment and promoting economic growth.

2. WEF nexus with CBE

Incorporating CBE into the WEF nexus (WEF-CBE) holds significant potential for addressing the intricate interconnections among these crucial sectors. Adopting CBE into WEF can enhance resource-use efficiency, facilitate effective waste management, and ensure long-term value preservation within this nexus. The CBE's holistic approach, combining concepts such as feedback systems, "cradle-to-cradle" principles, and closed-loop systems, enables us to create a more sustainable and resilient system (Khan et al., 2021; Tan and Lamers, 2021; Ncube et al., 2022). Treating and converting waste into bio-based materials and keeping products and materials in use for as long as possible can create a robust framework for promoting economic and environmental sustainability and lead to synergism among components (Wu et al., 2021; Kumar Sarangi et al., 2023). This integration meets the growing demand for bio-based materials in agriculture (MacArthur, 2013), as they are perceived to offer safer and more sustainable alternatives compared to synthetic products.

WEF-CBE offers various opportunities for sustainable resource management (Figure 1). For example, using wastewater from food production for irrigation can reduce the demand for freshwater resources, leading to more sustainable water use (Ansari et al., 2019; Geressu et al., 2020; Yue and Guo, 2021). On the one hand, a CBE principle to water management could involve using natural ecosystems, such as wetlands or riparian buffers, to filter and store water, which can help to reduce the need for expensive and energy-intensive water treatment systems (Geressu et al., 2020; Nepal et al., 2021). On the other hand, it can involve using water-efficient crops such as drought-tolerant varieties to reduce the water requirements for irrigation and using water-efficient technologies such as drip irrigation to reduce water loss and increase irrigation efficiency. Moreover, innovative technologies such as membrane filtration and reverse osmosis can help recover valuable resources (e.g., nutrients and energy) from wastewater.

In terms of nutrient management, bio-based materials (Giampietro, 2019; Jain et al., 2022; Mukhtar et al., 2023), such as biofertilizers, produced from agricultural waste and organic sources, have emerged as a promising alternative to synthetic fertilizers, providing a range of benefits for both crops and the environment (Figure 1). It can promote soil health and fertility without the negative environmental impacts associated with synthetic fertilizers, such as soil acidification, nutrient leaching, and water pollution. Moreover, biofertilizers can improve soil structure, promote beneficial microbial

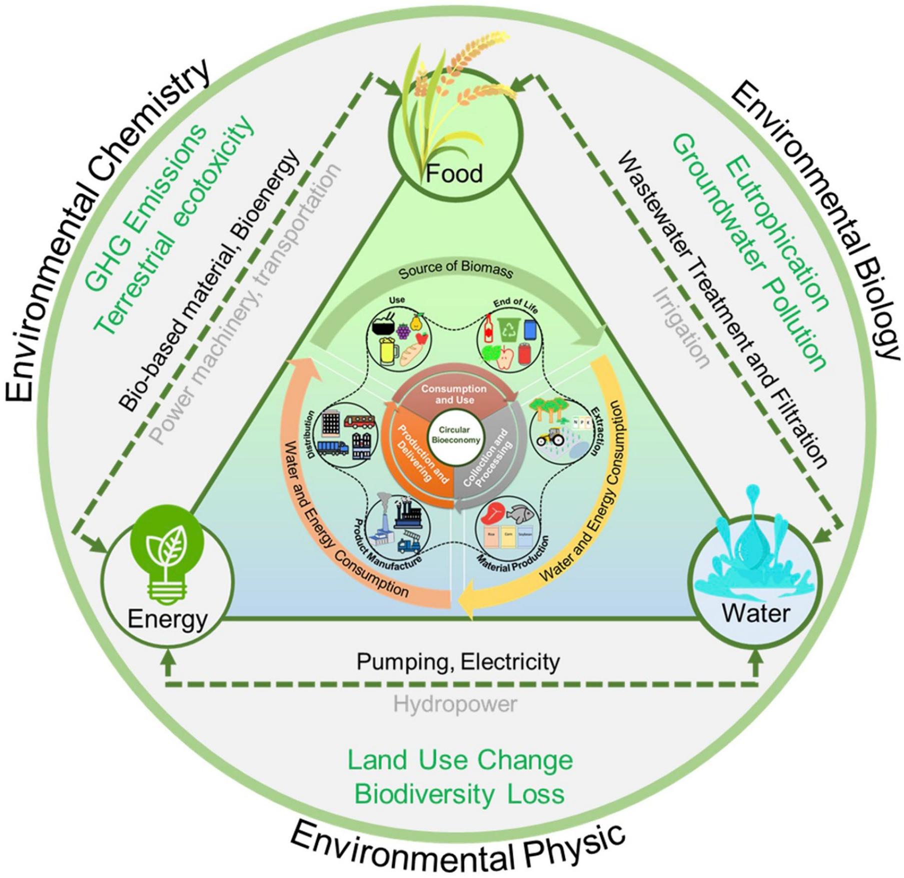

FIGURE 1
Synergies and trade-off of WEF nexus with circular bioeconomy.

activity, and reduce the risk of nutrient runoff (Giampietro, 2019; Yue and Guo, 2021; Peña-Torres et al., 2022). In addition to bio-based materials products, a range of other bio-based materials can be used to support sustainable agriculture practices, such as biopesticides and biochar. Biopesticides, a compound derived from natural sources such as plants or microbes, can be used to control pests and diseases, while biochar, a type of charcoal produced from organic waste material such as crop residues and animal manure, can be used to improve water retention and carbon sequestration (Jain et al., 2022; Osman et al., 2022). Furthermore, the application of bio-based materials can contribute to reduce GHG emissions and mitigate climate change impacts through potential carbon sequestration and reducing soil and water pollution (Lin et al., 2022b; Mukhtar et al., 2023).

The energy component of the WEF nexus plays a vital role in promoting sustainable agriculture, as it is required for power machinery, transport goods, and process products. The energy demand is expected to rise significantly due to increasing population, urbanization, industrialization, and climate change (van Ruijven et al., 2019; Ahmad and Zhang, 2020). However, the conventional energy used in agriculture contributes to GHG emissions, climate change, and other environmental problems. Agriculture is responsible for approximately ~21–37% of global GHG emissions annually, including methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2), with energy use accounting for a significant portion of these emissions (Mbow et al., 2019; Lin et al., 2022a). Therefore, to promote sustainable agriculture, it is essential to develop renewable energies and implement energy-efficient practices and technologies. For example, using renewable energies from solar, wind, and hydropower can reduce dependence on fossil fuels to meet the energy needs of agricultural operations and decrease GHG due to its eco-friendlier energies (Payet-Burin et al., 2019; Rahman et al., 2022). This manner can have substantial economic benefits, as renewable energy systems can provide a stable source of energy that is less vulnerable to price fluctuations and supply disruptions. On the other hand, energy-efficient practices and technologies, such as precision agriculture, improve the efficiency of the equipment and machinery, reduce energy consumption in buildings and facilities, and optimize irrigation systems, to reduce water and energy use (Gathala et al., 2020; Iddio et al., 2020; Lefers et al., 2020). These technologies can also help farmers to identify inefficient areas and implement targeted solutions to improve their operations. Regarding waste management, there are also opportunities to integrate energy and waste management systems in agriculture to produce bioenergy which can be used for transportation fuels, electricity, heat, and product (Giampietro, 2019; van Ruijven et al., 2019; Jain et al., 2022). For instance, biogas and biofuel production from agricultural waste and crops can provide a sustainable source of renewable energy that can be used to power farm operations, fed into the grid, transportation, and other applications. Moreover, anaerobic digestion can convert organic waste materials, such as animal manure, food waste, crop residues, and wastewater biosolids, into bioenergy and biochemicals (Lefers et al., 2020; Chew et al., 2021; Osman et al., 2022). Therefore, farmers can reduce their operating costs, improve their bottom line, and reduce their environmental impact by reducing energy consumption.

WEF-CBE aligns with key Sustainable Development Goals (SDGs), including Zero Hunger (SDG 2), Clean Water and Sanitation (SDG 6), Affordable and Clean Energy (SDG 7), Responsible Consumption and Production (SDG 12), and Climate Action (SDG 13). WEF-CBE promotes sustainable agriculture and food production by efficiently utilizing biological resources, reducing waste, and enhancing food security (Pastor et al., 2019; Ansari et al., 2021; Tan and Lamers, 2021; el-Ramady et al., 2022; Kumar Sarangi et al., 2023). It focuses on sustainable resource management, including water, to minimize pollution and conserve water resources. This can unlock new pathways towards achieving more resilient, resource-efficient, and sustainable water management to meet the socioeconomic needs of communities and ensure the long-term availability of high-quality water resource for future generations, which align with the long history of Mar del Plata (MDP) and New York City (NYC) water conference (Quentin Grafton et al., 2023). Moreover, it contributes to the sustainable management of blue, green, and grey water by optimizing freshwater, improving water retention in soil, and promoting wastewater treatment and reuse through practices like precision irrigation, regenerative agriculture, and innovative technologies. WEF-CBE supports the transition to clean and renewable energy sources through bioenergy from organic waste and biomass, reducing reliance on fossil fuels. It encourages responsible consumption and production patterns, aiming to minimize waste generation and optimize resource utilization. WEF-CBE contributes to climate action by reducing greenhouse gas emissions through sustainable practices and the use of renewable resources, promoting lower carbon footprints and climate-resilient strategies.

Previous studies have analyzed CBE practices in agriculture that have already been applied in several countries focusing on the efficient utilization and treatment of agricultural waste (Duan et al., 2020; Ngammuangtueng et al., 2020; Khan and Ali, 2022). For example, a study by Ngammuangtueng et al. (2020) assessed the nexus of water, food, and energy in Thailand's cassava and sugarcane supply chains. They highlighted the need to prioritize improvements in cultivation even better water and energy use efficiency are needed for a more sustainable bioeconomy. Another study from Khan and Ali (2022) indicated that CBE could be applied in Pakistan's agriculture sector by using residual agricultural waste as a biomass resource for generating valuable bio-products and bioenergy. This approach can help achieve higher standards of sustainability in the sector. Indeed, a study by Duan et al. (2020) reported that organic solid waste biorefinery is considered a promising approach for achieving a CBE in China, which can contribute to environmental protection and sustainable development by reducing greenhouse gas emissions and conserving biodiversity. Moreover, hydrothermal processing of microalgal biomass is regarded as a promising technology to generate a multitude of energy-based and value-added products (biochar, biofertilizers, and platform chemicals) (Behera et al., 2022). Utilizing algal biomass for hydrothermal processing makes it a viable bioresource providing ample opportunities to establish and integrate the value and supply chain products for addressing the issues linked to the combined nexus. This technology can accelerate the circular bioeconomy by providing sustainable energy and value-added platform solutions.

Additionally, Conservation Agriculture based Sustainable Intensification (CASI), exemplifying agricultural practices with broad socioeconomic implications, has diverse impacts, including increased productivity and income, resource efficiency, cost savings, environmental sustainability, social equity and empowerment, and climate change resilience (Dixon et al., 2019, 2020). These impacts align with the goals of the CBE and contribute to the efficient use of water, energy, and food resources. The success of CASI, as highlighted in the studies by Dixon et al. (2019, 2020), is evident through its adoption on over 15% of global cropland, including irrigated farming systems (e.g., Eastern Gangetic Plain) and rainfed systems. One key factor contributing to their success is the integration of conservation practices, such as reduced tillage, soil cover, and diversified cropping systems. These practices optimize water and energy use by enhancing water retention, reducing soil erosion, and minimizing energy-intensive activities. CASI also improves food production, addresses food security challenges, and builds climate resilience through sustainable intensification strategies to get higher crop yields while minimizing negative environmental impacts. The diversified cropping systems in CASI enhance resilience to climate variability and mitigate risks associated with monoculture systems. Furthermore, the scalability and adaptability of CASI to different agroecological conditions have facilitated its rapid adoption in various regions.

Implementing CBE into WEF nexus creates a range of conditions that promote resource efficiency, sustainability, and resilience. Firstly, a shift towards CBE fosters integrated and holistic approaches to manage water, energy, and food systems. This encourages synergistic interactions and optimizing resource allocation among the different sectors, minimizing waste and maximizing resource utilization. CBE promotes adopting practices and technologies that enhance resource efficiency within the WEF nexus. For example, water-efficient irrigation systems, renewable energy generation, and sustainable agricultural practices are implemented to minimize water and energy consumption while ensuring adequate food production. Moreover, WEF-CBE encourages innovation and collaboration among stakeholders. It creates opportunities to develop new technologies, business models, and value chains that promote resource efficiency and sustainability. This collaboration among different sectors, such as agriculture, energy, and water management, fosters knowledge-sharing, capacity-building, and co-creating solutions for integrated resource management.

3. Challenges and limitations

The WEF-CBE in agriculture offers significant benefits but also entails challenges and limitations. Balancing trade-offs and synergies within the nexus component is a major challenge (Putra et al., 2020; Wu et al., 2021; Zhao et al., 2021; Ding and Chen, 2023; Wang et al., 2023). For instance, using renewable energy from crops and agricultural waste may lead to competition for land use and potential conflicts between food and energy components (Dixon et al., 2010; Langeveld et al., 2014). The cultivation of biofuel feedstocks such as corn and sugarcane often demands substantial amounts of water, leading to increase pressure on water sources. This can worsen water scarcity in regions already facing water stress and create competition

10.3389/fsufs.2023.1207197

TABLE 1 Implications of WEF-CBE.

Strength	Weakness	Opportunity	Threat
Integration of different sectors and stakeholders for a holistic approach	Complex and challenging coordination between sectors	Innovation in WEF-CBE can create new markets and industries	Limited public and political awareness and support
Potential to reduce waste and emissions and increase resource efficiency	High initial investment and long-term implementation costs	Potential to increase food security and reduce poverty	Climate change impacts on water and energy availability
Enhancement of local economic development and employment opportunities	Limited availability and accessibility of CBE technologies and practice	Potential for sustainable energy production and reduced dependency on fossil fuels	Natural resources depletion and degradation
Reduction of GHG emissions and contribution to climate change mitigation	Lack of policy and regulatory framework to support WEF-CBE	Integration of traditional knowledge and local practices in WEF-CBE	Economic and political instability affecting investment and cooperation

between biofuel production and other dependent sectors such as agriculture and domestic water supply. Furthermore, biofuel production can contribute to land use changes and competition for arable land, potentially causing deforestation, loss of biodiversity, and displacement of local communities. On the one hand, adequate infrastructure, innovative and sustainable technologies, and economic stability to address food, water, and energy challenges holistically (Piacentino et al., 2019; Chang et al., 2020; Zhang et al., 2022; Osman et al., 2023; Wang et al., 2023). However, certain regions may lack suitable infrastructure and technologies, and the high cost can hinder small-scale farmer communities' adoption (Gilg and Barr, 2006; Gadenne et al., 2011; Tiefenbeck et al., 2013). On the other hand, investments in research, development, infrastructure, and training are necessary but can be costly and pose barriers to adoption. Innovative business models are needed to incentivize sustainable practices and technologies. Insufficient financial resources, technological expertise, and supportive policies and regulations further hinder achieving economic and environmental sustainability.

Implementing WEF-CBE may encounter socioeconomic and cultural challenges, which vary depending on the context and location (Dixon et al., 2020; Ngammuangtueng et al., 2020; Khan et al., 2021; Bottausci et al., 2022; Ncube et al., 2022). Limited awareness and understanding of the integration's potential benefits can hinder support from stakeholders and the public, making it difficult to secure necessary resources and funding. Moreover, adopting WEF-CBE may require changes in consumption and production patterns, which can face consumer resistance and producers hesitant to embrace new practices. Social equity and distributional impacts also present challenges, as improper implementation may result in uneven distribution of benefits and costs among different social groups, leading to conflicts and inequalities. Additionally, the WEF-CBE faces environmental limitations due to chemical, biological, and physical factors. Therefore, evaluating the WEF's strengths, weaknesses, opportunities, and threats is essential for understanding its potential (Table 1).

To overcome the challenges within WEF-CBE, collaboration and investment from governments, policymakers, and the private sector are crucial. Sustainable technologies, research, and development should be prioritized to address limitations and promote a holistic approach (Schöggl et al., 2020). Engaging local communities, stakeholders, and policymakers in planning and implementation is vital to ensure equitable distribution of benefits and even achieve economic and environmental sustainability (Klein et al., 2022). Capacity building and knowledge transfer programs are essential to increase understanding and awareness among stakeholders. These programs can disseminate best practices, case studies, and research findings through various platforms. Farmers, industry leaders, and policymakers can benefit from tailored capacity-building programs. Awareness campaigns can encourage public participation and support. Establishing a framework for monitoring, evaluating, and adapting policies and practices is crucial. This framework should consider environmental and socioeconomic aspects and involve all relevant stakeholders. Through fostering collaboration among different sectors, it promotes innovation and co-creation of knowledge and practices to enhance sustainability.

4. Conclusion

Altogether, the WEF-CBE in agriculture provides a comprehensive framework for promoting sustainable resource management, creating collaboration between different sectors, and advancing CBE practices. The potential benefits of incorporating biological processes into the circular economy model, provide opportunities for the sustainable production of food, energy, and other goods, to achieve food security, sustainable economic growth, and reduced environmental impacts, making it a worthwhile endeavor. Additionally, this approach can provide new income streams for farmers, boost rural development, and support the achievement of SDGs. However, to fully realize the potential of this integration, there is a need for supportive policy and institutional frameworks, significant infrastructure investments, the development of new technologies, and a better understanding of social and cultural constraints. Finally, public engagement and awareness-raising campaigns through capacity-building and knowledge transfer programs are necessary to build support for the WEF-CBE and encourage behavioral change.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AA, SW, and TT: conceptualization. AA: writing – original draft. AA, SW, AP, MT, NN, MH, TA, SS, TM, and TT: review and editing.

All authors listed have contributed to the work and approved the submitted version for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Ahmad, T., and Zhang, D. (2020). A critical review of comparative global historical energy consumption and future demand: the story told so far. *Energy Rep.* 6, 1973–1991. doi: 10.1016/j.egyr.2020.07.020

Ansari, A., Kato, T., and Fitriah, A. (2019). Simulating streamflow through the SWAT model in the Keduang sub-watershed, Wonogiri regency, Indonesia. *Agritech.* 39, 60–69. Available at: https://jurnal.ugm.ac.id/agritech/article/view/42884/25461

Ansari, A., Lin, Y.-P., and Lur, H.-S. (2021). Evaluating and adapting climate change impacts on rice production in Indonesia: a case study of the Keduang subwatershed, Central Java. *Environments* 8:117. doi: 10.3390/environments8110117

Behera, B., Selvam, S. M., and Balasubramanian, P. (2022). Hydrothermal processing of microalgal biomass: circular bio-economy perspectives for addressing food-water-energy nexus. *Bioresour. Technol.* 359:127443. doi: 10.1016/j.biortech.2022.127443

Biggs, E. M., Bruce, E., Boruff, B., Duncan, J. M. A., Horsley, J., Pauli, N., et al. (2015). Sustainable development and the water-energy-food nexus: a perspective on livelihoods. *Environ. Sci. Policy* 54, 389–397. doi: 10.1016/j.envsci.2015.08.002

Bottausci, S., Midence, R., Serrano-Bernardo, F., and Bonoli, A. (2022). Organic waste management and circular bioeconomy: a literature review comparison between Latin America and the European Union. *Sustainability* 14:1661. doi: 10.3390/su14031661

Braun, R., Hertweck, D., and Eicker, U. (2022). An approach to cluster the research field of the food-energy-water nexus to determine modeling capabilities at different levels using text mining and cluster analysis. *Energy Nexus* January 2015:100101. doi: 10.1016/j.nexus.2022.100101

Chang, N.-B., Hossain, U., Valencia, A., Qiu, J., and Kapucu, N. (2020). The role of food-energy-water nexus analyses in urban growth models for urban sustainability: a review of synergistic framework. *Sustain. Cities Soc.* 63:102486. doi: 10.1016/j.scs.2020.102486

Chew, K. R., Leong, H. Y., Khoo, K. S., Vo, D.-V. N., Anjum, H., Chang, C.-K., et al. (2021). Effects of anaerobic digestion of food waste on biogas production and environmental impacts: a review. *Environ. Chem. Lett.* 19, 2921–2939. doi: 10.1007/s10311-021-01220-z

Ding, T., and Chen, J. (2023). Evaluating supply-demand matching of ecosystem services considering water-energy-food nexus and synergies/trade-offs in the Hangzhou of China. *Environ. Sci. Pollut. Res.* 30, 54568–54585. doi: 10.1007/s11356-023-26055-9

Dixon, J. M., Huttner, E., Reeves, T., El Mourid, M., Timsina, J., Loss, S., et al. (2019). Interdisciplinary research methods for international research on conservation agriculture based sustainable intensification (CASI). In *Agricultural Science, special issue: ACIAR at work: interdisciplinary research into smallholder farming systems, combined*. eds. J. M. Dixon and S. G. Coffey 30, 64–81. Available at: https://aciar.gov.au/sites/default/files/web_j_ag_sci_vols_302_31_1_special_issue.pdf.

Dixon, J., Li, X., Msangi, S., Amede, T., Bossio, D., Ceballos, H., et al. (2010). Feed, food and fuel: competition and potential impacts on small-scale crop–lisvestock–energy farming systems. CGIAR Syst Livest Program Proj Report SLP, Addis Ababa, Ethiop [internet], 114. Available at: https://cgspace.cgiar.org/bitstream/handle/10568/3018/Food_feed_fuelfinal.pdf?sequence=1.

Dixon, J., Rola-Rubzen, M. F., Timsina, J., Cummins, J., and Tiwari, T. P. (2020). Socioeconomic impacts of conservation agriculture based sustainable intensification (CASI) with particular reference to South Asia. In *No-Till Farming Syst. Sustain. Agric. Chall. Oppor*. eds. Y. Dang, R. Dalal and N. Menzies Switzerland: Springer, Cham. 377–394. doi: 10.1007/978-3-030-46409-7_22

Duan, Y., Pandey, A., Zhang, Z., and Kumar, M. (2020). Industrial crops & products organic solid waste biorefinery: sustainable strategy for emerging circular bioeconomy in China. *Ind. Crop. Prod.* 153:112568. doi: 10.1016/j.indcrop.2020.112568

El-Ramady, H., Brevik, E. C., Bayoumi, Y., Shalaby, T. A., el-Mahrouk, M. E., Taha, N., et al. (2022). An overview of agro-waste management in light of the water-energy-waste nexus. *Sustainability* 14:15717. doi: 10.3390/su142315717

Gadenne, D., Sharma, B., Kerr, D., and Smith, T. (2011). The influence of consumers' environmental beliefs and attitudes on energy saving behaviours. *Energy Policy* 39, 7684–7694. doi: 10.1016/j.enpol.2011.09.002

Gathala, M. K., Laing, A. M., Tiwari, T. P., Timsina, J., Islam, S., Bhattacharya, P. M., et al. (2020). Energy-efficient, sustainable crop production practices benefit smallholder farmers and the environment across three countries in the eastern Gangetic Plains, South Asia. *J. Clean. Prod.* 246:118982. doi: 10.1016/j.jclepro.2019.118982

Geressu, R., Siderius, C., Harou, J. J., Kashaigili, J., Pettinotti, L., and Conway, D. (2020). Assessing river basin development given water-energy-food-environment interdependencies. *Earth's Future* 8:e2019EF001464. doi: 10.1029/2019EF001464

Giampietro, M. (2019). On the circular bioeconomy and decoupling: implications for sustainable growth. *Ecol. Econ.* 162, 143–156. doi: 10.1016/j.ecolecon.2019.05.001

Gilg, A., and Barr, S. (2006). Behavioural attitudes towards water saving? Evidence from a study of environmental actions. *Ecol. Econ.* 57, 400–414. doi: 10.1016/j.ecolecon.2005.04.010

Hetemäki, L., Hanewinkel, M., Muys, B., Ollikainen, M., Palahí, M., Trasobares, A., et al. (2017). *Leading the way to a European circular bioeconomy strategy*. Vol. *5*. European Forest Institute Joensuu, Finland.

Iddio, E., Wang, L., Thomas, Y., McMorrow, G., and Denzer, A. (2020). Energy efficient operation and modeling for greenhouses: a literature review. *Renew. Sust. Energ. Rev.* 117:109480. doi: 10.1016/j.rser.2019.109480

Jain, A., Sarsaiya, S., Awasthi, M. K., Singh, R., Rajput, R., Mishra, U. C., et al. (2022). Bioenergy and bio-products from bio-waste and its associated modern circular economy: current research trends, challenges, and future outlooks. *Fuel* 307:121859. doi: 10.1016/j.fuel.2021.121859

Khan, F., and Ali, Y. (2022). Moving towards a sustainable circular bio-economy in the agriculture sector of a developing country. *Ecol. Econ.* 196:107402. doi: 10.1016/j.ecolecon.2022.107402

Khan, F., Ali, Y., Kardung, M., Cingiz, K., Costenoble, O., Delahaye, R., et al. (2021). Development of the circular bioeconomy: drivers and indicators. *Ecol. Econ.* 196, 1–24. doi: 10.1016/j.ecolecon.2022.107402

Klein, O., Nier, S., and Tamásy, C. (2022). Towards a circular bioeconomy? Pathways and spatialities of agri-food waste valorisation. *Tijdschr. Econ. Soc. Geogr.* 113, 194–210. doi: 10.1111/tesg.12500

Kumar Sarangi, P., Subudhi, S., Bhatia, L., Saha, K., Mudgil, D., Prasad Shadangi, K., et al. (2023). Utilization of agricultural waste biomass and recycling toward circular bioeconomy. *Environ. Sci. Pollut. Res.* 30, 8526–8539. doi: 10.1007/s11356-022-20669-1

Langeveld, H., Dixon, J., and van Keulen, H. (2014). *Biofuel cropping systems: carbon, land and food*. New York: Routledge.

Lefers, R. M., Tester, M., and Lauersen, K. J. (2020). Emerging technologies to enable sustainable controlled environment agriculture in the extreme environments of Middle East-North Africa coastal regions. *Front. Plant Sci.* 11:801. doi: 10.3389/fpls.2020.00801

Li, M., Li, H., Fu, Q., Liu, D., Yu, L., and Li, T. (2021). Approach for optimizing the water-land-food-energy nexus in agroforestry systems under climate change. *Agric. Syst.* 192:103201 Available at: https://www.sciencedirect.com/science/article/pii/S0308521X21001542

Lin, Y.-P., Ansari, A., Ngoc-Dan Cao, T., Shiau, Y.-J., Lur, H.-S., Muzaffar, A., et al. (2022a). Using inhibitors to trade greenhouse gas emission for ammonia losses in paddy soil: a zero-sum game. *Environ. Technol. Innov.* 28:102547 Available at: https://www.sciencedirect.com/science/article/pii/S2352186422001419

Lin, Y.-P., Ansari, A., Wunderlich, R. F., Lur, H.-S., Ngoc-Dan Cao, T., Mukhtar, H, et al. (2022b). Assessing the influence of environmental niche segregation in ammonia oxidizers on N_2O fluxes from soil and sediments. *Chemosphere* 289: 133049. doi: 10.1016/j.chemosphere.2021.133049

Lynch, J., Cain, M., Frame, D., and Pierrehumbert, R. (2021). Agriculture's contribution to climate change and role in mitigation is distinct from predominantly fossil CO2-emitting sectors. *Front. Sustain. Food Syst.* 4, 1–9. doi: 10.3389/fsufs.2020.518039

MacArthur, E. (2013). *Towards the circular economy, economic and business rationale for an accelerated transition*. Ellen MacArthur Found Cowes, UK; 21–34.

Mbow, C., Rosenzweig, C., Barioni, L. G., Benton, T. G., Herrero, M., Krishnapillai, M., et al. (2019). Food security. Clim Chang L an IPCC Spec Rep Clim Chang Desertif L Degrad Sustain L Manag food Secur Greenh gas fluxes Terr Ecosyst. Retrieved from IPCC [Intergovernmental Panel Climate Change].

Mukhtar, H., Wunderlich, R. F., Muzaffar, A., Ansari, A., Shipin, O. V., Cao, T. N.-D., et al. (2023). Soil microbiome feedback to climate change and options for mitigation. *Sci. Total Environ.* 882: 163412. doi: 10.1016/j.scitotenv.2023.163412

Ncube, A., Sadondo, P., Makhanda, R., Mabika, C., Beinisch, N., Cocker, J., et al. (2022). Circular bioeconomy potential and challenges within an African context: from theory to practice. *J. Clean. Prod.* 367:133068. doi: 10.1016/j.jclepro.2022.133068

Nepal, S., Neupane, N., Belbase, D., Pandey, V. P., and Mukherji, A. (2021). Achieving water security in Nepal through unravelling the water-energy-agriculture nexus. *Int. J. Water Resour. Dev.* 37, 67–93. doi: 10.1080/07900627.2019.1694867

Ngammuangtueng, P., Jakrawatana, N., and Gheewala, S. H. (2020). Nexus resources efficiency assessment and management towards transition to sustainable bioeconomy in Thailand. *Resour. Conserv. Recycl.* 160:104945. doi: 10.1016/j.resconrec.2020.104945

Osman, A. I., Chen, L., Yang, M., Msigwa, G., Farghali, M., Fawzy, S., et al. (2023). Cost, environmental impact, and resilience of renewable energy under a changing climate: a review. *Environ. Chem. Lett.* 21, 741–764. doi: 10.1007/s10311-022-01532-8

Osman, A. I., Fawzy, S., Farghali, M., El-Azazy, M., Elgarahy, A. M., Fahim, R. A., et al. (2022). Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review. *Environ. Chem. Lett.* 20, 2385–2485. doi: 10.1007/s10311-022-01424-x

Pastor, A. V., Palazzo, A., Havlik, P., Biemans, H., Wada, Y., Obersteiner, M., et al. (2019). The global nexus of food–trade–water sustaining environmental flows by 2050. *Nat. Sustain.* 2, 499–507. doi: 10.1038/s41893-019-0287-1

Payet-Burin, R., Kromann, M., Pereira-Cardenal, S., Strzepek, K. M., and Bauer-Gottwein, P. (2019). WHAT-IF: an open-source decision support tool for water infrastructure investment planning within the water–energy–food–climate nexus. *Hydrol. Earth Syst. Sci.* 23, 4129–4152. doi: 10.5194/hess-23-4129-2019

Peña-Torres, D., Boix, M., and Montastruc, L. (2022). Optimization approaches to design water-energy-food nexus: a litterature review. *Comput. Chem Eng.* 167:108025. doi: 10.1016/j.compchemeng.2022.108025

Piacentino, A., Duic, N., Markovska, N., Mathiesen, B. V., Guzović, Z., Eveloy, V., et al. (2019). Sustainable and cost-efficient energy supply and utilisation through innovative concepts and technologies at regional, urban and single-user scales. *Energy* 182, 254–268. doi: 10.1016/j.energy.2019.06.015

Putra, M. P. I. F., Pradhan, P., and Kropp, J. P. (2020). A systematic analysis of water-energy-food security nexus: a south Asian case study. *Sci. Total Environ.* 728:138451. doi: 10.1016/j.scitotenv.2020.138451

Quentin Grafton, R., Biswas, A. K., Bosch, H., Fanaian, S., Gupta, J., Revi, A., et al. (2023). Goals, progress and priorities from Mar del Plata in 1977 to New York in 2023. *Nat. Water* 1, 230–240. doi: 10.1038/s44221-023-00041-4

Rahman, M. M., Khan, I., Field, D. L., Techato, K., and Alameh, K. (2022). Powering agriculture: present status, future potential, and challenges of renewable energy applications. *Renew. Energy* 188, 731–749. doi: 10.1016/j.renene.2022.02.065

Schöggl, J.-P., Stumpf, L., and Baumgartner, R. J. (2020). The narrative of sustainability and circular economy-a longitudinal review of two decades of research. *Resour. Conserv. Recycl.* 163:105073. doi: 10.1016/j.resconrec.2020.105073

Siderius, C., Biemans, H., Kashaigili, J., and Conway, D. (2022). Water conservation can reduce future water-energy-food-environment trade-offs in a medium-sized African river basin. *Agric. Water Manag.* 266:107548. doi: 10.1016/j.agwat.2022.107548

Stegmann, P., Londo, M., and Junginger, M. (2020). The circular bioeconomy: its elements and role in European bioeconomy clusters. *Resour. Conserv. Recycl. X* 6:100029. doi: 10.1016/j.rcrx.2019.100029

Tan, E. C. D., and Lamers, P. (2021). Circular bioeconomy concepts — a perspective. *Front. Sustain.* 2, 1–8. doi: 10.3389/frsus.2021.701509

Tiefenbeck, V., Staake, T., Roth, K., and Sachs, O. (2013). For better or for worse? Empirical evidence of moral licensing in a behavioral energy conservation campaign. *Energy Policy* 57, 160–171. doi: 10.1016/j.enpol.2013.01.021

van Ruijven, B. J., de Cian, E., and Sue Wing, I. (2019). Amplification of future energy demand growth due to climate change. *Nat. Commun.* 10:2762. doi: 10.1038/s41467-019-10399-3

Wang, X., Dong, Z., and Sušnik, J. (2023). System dynamics modelling to simulate regional water-energy-food nexus combined with the society-economy-environment system in Hunan Province, China. *Sci. Total Environ.* 863:160993. doi: 10.1016/j.scitotenv.2022.160993

Wu, L., Elshorbagy, A., Pande, S., and Zhuo, L. (2021). Trade-offs and synergies in the water-energy-food nexus: the case of Saskatchewan, Canada. *Resour. Conserv. Recycl.* 164:105192. doi: 10.1016/j.resconrec.2020.105192

Yue, Q., and Guo, P. (2021). Managing agricultural water-energy-food-environment nexus considering water footprint and carbon footprint under uncertainty. *Agric. Water Manag.* 252:106899. doi: 10.1016/j.agwat.2021.106899

Zhang, L., Xu, M., Chen, H., Li, Y., and Chen, S. (2022). Globalization, green economy and environmental challenges: state of the art review for practical implications. *Front. Environ. Sci.* 10:199. doi: 10.3389/fenvs.2022.870271

Zhao, D., Liu, J., Sun, L., Ye, B., Hubacek, K., Feng, K., et al. (2021). Quantifying economic-social-environmental trade-offs and synergies of water-supply constraints: an application to the capital region of China. *Water Res.* 195:116986. doi: 10.1016/j.watres.2021.116986