Archives of Hydro-Engineering and Environmental Mechanics 72 (2025), pp. 15–27, doi: 10.2478/heem-2025-0002

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ARCHIVES OF HYDRO-ENGINEERING AND ENVIRONMENTAL MECHANICS

Published since 1954

ISSN 1231–3726

Resource and Ecological Principles of Irrigation in Current Conditions

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(Received 227 January 2025; revised 28 April 2025)

Abstract. Irrigation development focused on implementing ecologically sound and nature-based solutions was explored. This approach is crucial in addressing the pressing need to conserve water and electricity resources, aligning irrigated farming practices with current global challenges and sustainable development goals. Unlike traditional methods, it is essential to view water and electricity resources as integral components of irrigation efficiency from a resource-ecological perspective. A computer experiment involving predictive and simulation modeling was conducted to assess the feasibility and potential cost savings of adopting resource-ecological principles in irrigation practices. The study evaluated the resource-ecological efficiency of different sprinkler irrigation regimes based on irrigation reliability, which measures deviations from projected irrigation and watering rates. Multicriteria regression analysis revealed a strong correlation ($R^2 = 0.874$) among various factors influencing irrigation efficiency. Results indicated that implementing different levels of irrigation reliability could significantly improve technological efficiency, with crop productivity reductions ranging from 10.80% to 18.06% and water and electricity cost savings of 27% to 48%. These findings support the integration of nature-based and ecologically effective irrigation solutions to promote sustainable agriculture in the face of global challenges such as climate change, water scarcity, food insecurity, and energy shortages.

Key words: resource-ecological principles, water resources, electricity resources, irrigation, modern conditions

1. Introduction

Current global challenges such as climate change, water scarcity, food insecurity, and energy crises necessitate adaptation by the world community, including Ukraine, to address these pressing issues. This adaptation is crucial for enhancing the overall efficiency of various economic sectors, particularly agriculture, in order to meet sustainable development goals and ensure the well-being of future generations (Handbook of Research 2023, National Council for the Recovery of Ukraine from the War 2022, FAO 2019, United Nations 2015).

A significant portion of Ukraine's territory, including agricultural lands, is situated in high-risk agricultural zones with limited natural moisture. The cultivation of crops on these lands requires irrigation, especially as the area of high-risk agriculture in Ukraine has expanded due to climate change, now encompassing approximately 18 to 20 million hectares (Ukrinform 2021). Irrigated lands are valuable assets for agricultural production, offering significantly higher crop yields compared to non-irrigated lands.

Given these circumstances, irrigation has emerged as a key tool to mitigate the adverse effects of climate change on the agricultural sector. However, implementing irrigation incurs substantial water, electricity, and other resource costs. To ensure the sustainable development and recovery of irrigation practices, it is essential to embrace ecologically sound and nature-based solutions. These solutions are vital for enabling agricultural production to adapt to global challenges and achieve sustainable development goals (Rokochynskiy et al 2020b, Rokochynskyi et al 2025b).

In 2019, the Cabinet of Ministers of Ukraine approved the Strategy of Irrigation and Drainage in Ukraine until 2030 as a significant step towards the restoration of hydrotechnical reclamation, particularly irrigation (Cabinet of Ministers of Ukraine 2019). In 2020, a plan for its implementation was adopted. In October 2021, the Cabinet of Ministers of Ukraine approved the Strategy for Environmental Security and Adaptation to Climate Change until 2030 to address the needs for adapting economic sectors to climate change (Cabinet of Ministers of Ukraine 2021). This is the first national document to provide a legislative framework for systematic and long-term adaptation to climate change.

In 2019, Ukraine ranked 125th among 181 countries in the world in terms of available drinking water reserves. Even more problems are caused by climate change, and now by full-scale war. What is the situation with water in Ukraine on the regional level now under natural conditions is shown in Fig. 1.

In 2024, there were a record number of days with extremely high temperatures over the past 10 years. Ukraine has never seen such an intense and prolonged heat wave. Precipitation deficits averaged 40 to 60% of normal, with Kyiv region receiving less than 50% of normal precipitation, and Kherson, Mykolaiv, Dnipro, and Kharkiv regions receiving less than 16–20% of normal over 100 days. Only the western regions received between 70 and 120% of the typical rainfall rates over the three summer months. The lack of natural moisture in Ukraine's soils is already having a negative impact on land productivity and agricultural production efficiency, with the Ministry of Agrarian Policy reporting that more than 70% of crops are in danger of being damaged by a decline in moisture availability.

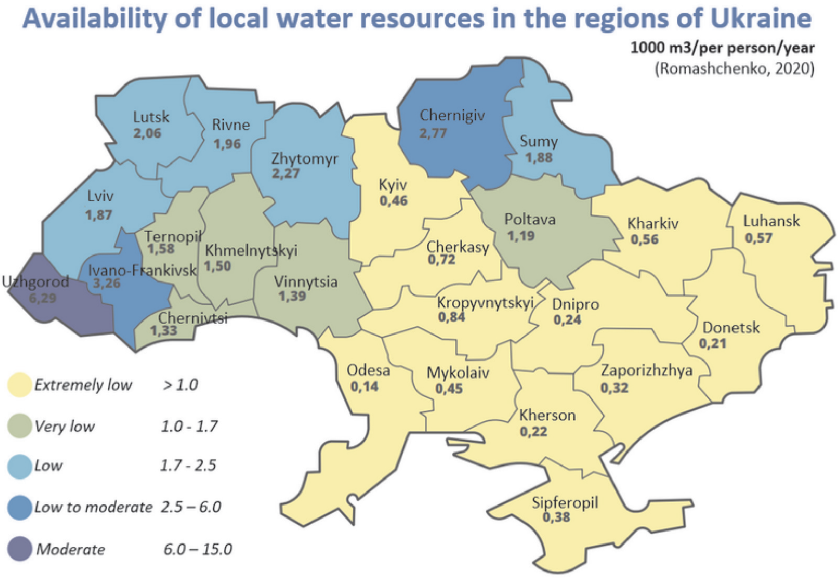

Fig. 1. Analysis of the impact of climate changes on water resources of Ukraine. Source: In UKR. EcoAction 2021, https://bit.ly/3CIcRkn

Due to hostilities and temporary occupation, Ukraine has lost over 25% of its total sown area. The majority of these temporarily lost areas are high-productivity irrigated lands in the eastern and southern regions of Ukraine. The detonation of the Kakhovka Hydroelectric Power Plant by Russian troops further reduced the availability of sown areas and exacerbated the issue of water shortage for irrigation purposes (Cabinet of Ministers of Ukraine 2023). The Kakhovka Reservoir played a crucial role in providing irrigation in the southern regions of Ukraine, particularly in the left bank Kherson region, and partially in Dnipropetrovsk and Zaporizhzhia regions. The challenge of ensuring irrigation with sufficient electricity remains a pressing issue.

In the context of climate change and escalating water, energy, and food crises, prioritizing ecologically effective and nature-based measures is essential. These measures can address societal needs and social challenges in an environmentally friendly manner, aligning with the principles of sustainable development that focus on more efficient use of resources, especially water and electricity (FAO 2018).

To achieve and maintain food security in the face of resource scarcity, adopting ecologically effective and nature-based solutions to enhance irrigation efficiency is crucial. This can be accomplished through the development of resource-saving technologies and measures that prioritize water and electricity while ensuring proper irrigation of crops (Rokochinskiy et al 2020a, Rokochinskiy et al 2025a, Korobiichuk et al 2017, Turcheniuk et al 2023, Kuzmych et al 2023a, b, c).

In recent years, there has been a trend in the United States of consciously reducing water consumption for irrigation. Farmers prioritize saving scarce and expensive water and electricity resources, even at the cost of partial crop yield losses (Sheldon et al 2023, Balasubramanya et al 2022, Widmar 2021). Similar practices, known as "deficit irrigation," are employed globally (Li et al 2023, Li et al 2022, Yang et al 2022, Liu et al 2021).

Given the current state of affairs, research focused on scientifically justifying the feasibility of resource-saving solutions and their impact on irrigation efficiency and agricultural productivity is crucial to achieving sustainable development goals.

Therefore, the aim of this research is to provide a rationale for the resource-ecological principles of feasibility and the levels of water and electricity cost reduction when implementing irrigation as an ecologically effective and nature-based solution for sustainable crop production in the face of global challenges such as climate change, water scarcity, food insecurity, and energy crises.

2. Study Materials and Methods

Modern alterations in the operational conditions of irrigation systems necessitate revisions in their design and construction methods, which should be based on a resource-centered approach. Innovative techniques for the construction and operation of irrigation systems, along with improving the regime and technological aspects of the irrigation process, must be adapted to contemporary changes. These adaptations should not only evaluate the effectiveness of technical solutions but also consider the actual operational conditions of the facility, the level and direction of agricultural production, and, most importantly, the resources required to sustain it.

To assess the overall effectiveness of sprinkler irrigation, a computer experiment was conducted (Kovalenko et al 2022) using various irrigation regimes to determine the feasibility and potential for reducing water and electricity consumption during irrigation. The experiment utilized data from an evaluation of a vibrating filter-settler used for purifying water of varying contamination levels at the agricultural enterprise LLC "C-Rostok" in the Kherson region of Ukraine (Rokochinskiy et al 2020a).

The LLC "C-Rostok" soils consist of southern low-humus black soils, and crops are irrigated using the "Fregat" sprinkler machines, specifically the DMU-Bnm463--57-01 modification. The main agricultural activities involve the cultivation of grain, technical, and vegetable crops.

For the experiment, a software program titled "Software Complex for Substantiation of Design Decisions in the Creation and Operation of Water Management and Reclamation Facilities" was employed (Koptiuk et al 2023). This program is based on models that simulate the climatic conditions and meteorological regimes of the area, the water regime, and water regulation technologies for reclaimed lands, as well as the productivity of these lands. These models are used for predictive evaluations of various variables and parameters related to the overall efficiency of the facility's operation. The application of these variables and parameters follows the industry-specific standards set by the State Agency of Water Resources of Ukraine (Koptiuk et al 2023, Kuzmych 2023, Rokochynskiy et al 2011, Rokochynskiy et al 2004, Rokochynskiy et al 2006).

The inputs for the computer experiment are as follows: the location is the Kherson region, within the natural-climatic Steppe zone. The vegetation periods are categorized based on heat and moisture availability as per (Rokochinskiy et al 2020a, Rokochynskiy et al 2006), with classifications ranging from very wet (p = 10%) to very dry (p = 90%). The soil conditions consist of southern low-humus black soils. The cultivated crops, as part of the project crop rotation, and their respective area shares are: perennial grasses for green mass (0.4), vegetables like tomatoes (0.2), winter wheat for grain (0.2), and corn for grain (0.2). The method of irrigation used is sprinkler irrigation.

The data for the computer experiment, which include watering rates and electricity costs under different sprinkler irrigation regimes for the project crop rotation, are detailed in Table 1. To assess the studied irrigation regimes, a metric called the *level of irrigation provision*, φ (%), was introduced. This indicator – the *level of irrigation provision*, expressed as a percentage, reflects how closely the studied sprinkling regimes align with the project regime. Specifically, it compares the watering rates (m, $m^3 \cdot ha^{-1}$) – in this case, this is the *level of irrigation provision according to the watering rates*, φ_m (%), and irrigation rates (m, $m^3 \cdot ha^{-1}$) – in this case, this is the *level of irrigation provision according to the irrigation rate*, φ_M (%), of a particular irrigation regime to their corresponding project values.

The sprinkler irrigation regimes with varying levels of irrigation provision that were considered as the primary options in the study are as follows:

- *Control option*: Project sprinkler irrigation regime with the level of irrigation provision according to the irrigation rate $\varphi_M = 100\%$;
- *Studied option No 1*: Sprinkler irrigation regime with the level of irrigation provision according to the irrigation rate $\varphi_M = 73\%$;
- *Studied option No 2*: Sprinkler irrigation regime with the level of irrigation provision according to the irrigation rate $\varphi_M = 70\%$
- *Studied option No 3*: Sprinkler irrigation regime with the level of irrigation provision according to the irrigation rate $\varphi_M = 67\%$
- *Studied option No 4*: Sprinkler irrigation regime with the level of irrigation provision according to the irrigation rate $\varphi_M = 62\%$;
- *Studied option No 5*: Sprinkler irrigation regime with the level of irrigation provision according to the irrigation rate $\varphi_M = 52\%$.

Table 1. Watering rates and electricity expenses associated with water supply across different sprinkler irrigation regimes for the planned crop rotation

Crop and indicator		Level of irrigation provision according to the irrigation rate (φ_M, %)					
		100% (project)	73%	70%	67%	62%	52%
perennial grasses for green mass	watering rate m, ($m^3 \cdot ha^{-1}$)	600	440	420	400	360	300
	electricity costs for pumping watering rate ω ($kWh \cdot ha^{-1}$)	200	147	140	133	120	100
vegetables (tomatoes)	watering rate m, ($m^3 \cdot ha^{-1}$)	540	400	380	360	350	300
	electricity costs for pumping watering rate ω ($kWh \cdot ha^{-1}$)	180	133	127	120	117	100
winter cereals for grain	watering rate m, ($m^3 \cdot ha^{-1}$)	380	270	260	250	240	200
	electricity costs for pumping watering rate ω ($kWh \cdot ha^{-1}$)	127	90	87	83	80	67
winter corn for grain	watering rate m, ($m^3 \cdot ha^{-1}$)	420	300	290	280	260	220
	electricity costs for pumping watering rate ω ($kWh \cdot ha^{-1}$)	140	100	97	93	87	73

Source: the data from the study

3. Result and Discussion

An important aspect of evaluating irrigation efficiency is selecting and justifying criteria that cover various facets of the process. To address this, a multiple criteria correlation-regression analysis was conducted. This type of analysis helps determine the strength of the relationship between different indicators and allows for the exclusion of those with minimal impact, thus validating the use of selected indicators as criteria for assessing irrigation efficiency.

The results from the multiple criteria correlation-regression analysis show a notable degree of correlation among different indicators that reflect various aspects of irrigation efficiency (Table 2). These indicators include:

- φ_M: Level of irrigation provision according to the irrigation rate
- M: Irrigation rate
- W: Electricity costs for pumping irrigation rate
- Y: Crop rotation productivity
- M_W: Overall use of water and electricity resources
- ΔY: Reduction in crop rotation productivity at different options of irrigation provision level

Table 2. Matrix of pairwise correlation coefficients between indicators characterizing the irrigation efficiency (coefficient of determination – $R^2 = 0.873$)

Indicator	φ_M	M	W	Y	M_W	ΔY
φ_M	1.000	0.915	0.895	0.876	–0.906	0.883
M	0.915	1.000	0.952	0.887	–0.937	0.880
W	0.895	0.952	1.000	0.885	–0.915	0.880
Y	0.876	0.887	0.885	1.000	–0.835	0.872
M_W	–0.906	–0.937	–0.915	–0.835	1.000	–0.874
ΔY	0.883	0.880	0.880	0.872	–0.874	1.000

Source: the data from the study

The overall correlation coefficient between the main disparate efficiency indicators is $R = 0.935$, which, like the pairwise correlation coefficients, is quite high, mean squared error of the regression equation –6.11 indicates a relatively insignificant deviation of the sample mean from the true value of the measured quantity. This indicates a strong relationship among these indicators and supports their use as criteria for evaluating the efficiency of sprinkler irrigation across various irrigation regimes. The results enable predictions of sprinkler irrigation effectiveness at different levels of irrigation provision.

The results of Table 2 confirm the feasibility of using the considered indicators as criteria for assessing the effectiveness of different irrigation regimes that correspond to different levels of irrigation provision.

Forecasting and simulation modeling for the typical vegetation periods and cultivated crops reveal variations in the resource-ecological (technological) effectiveness of irrigation. The values of irrigation rates and associated electricity costs for the different sprinkler irrigation regimes, which vary in irrigation sufficiency, have been determined. Additionally, the changes in crop yields, which represent the main output of agricultural production, have been assessed.

Figure 2 illustrates the results of calculations for winter wheat, a primary crop of LLC "C-Rostok." It shows the dynamics of changes in irrigation rates, electricity costs, and crop yields across different irrigation provision levels and typical vegetation periods, ranging from very wet ($p = 10\%$) to very dry ($p = 90\%$) (Rokochinskiy et al 2020a, Rokochynskiy et al 2006).

The data presented in Figure 2 obtained as the results of forecasting and simulation modelling during the implementation of a machine experiment by using the "Software package for substantiation of project decisions during the creation and operation of water management and reclamation facilities". This software package is a set of computer programs based on optimization, economic, mathematical, and forecasting and simulation methods and models, the use of which is regulated by the relevant industry standards of the State Agency of Water Resources of Ukraine. These data reveal a clear trend: as irrigation rates and electricity costs decrease, winter wheat yields also decline. However, the reduction in resource consumption (water and electricity) is more pronounced than the decrease in yields. Notably, during drier vegetation

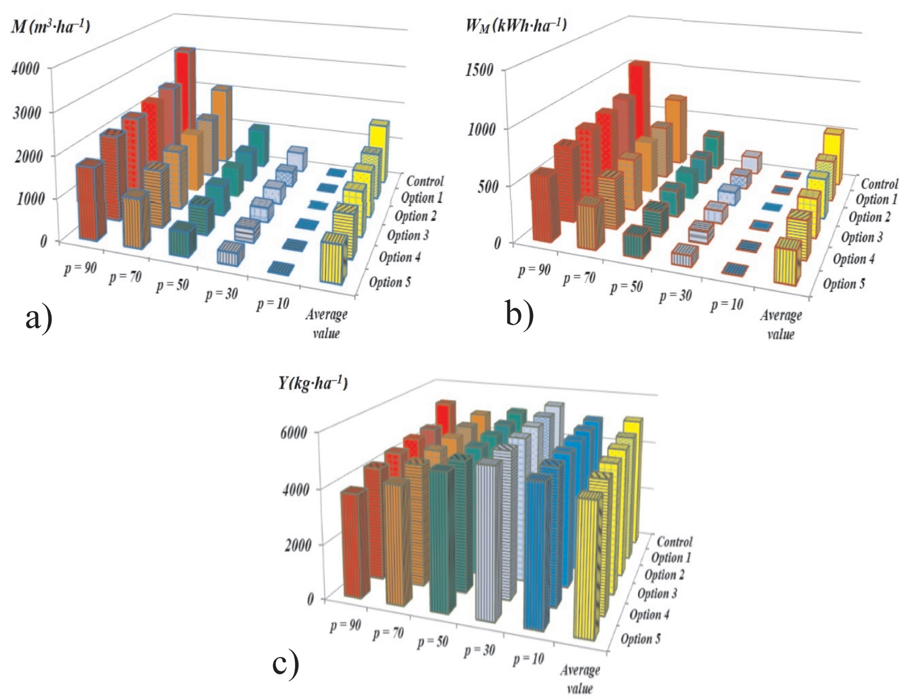

Fig. 2. The changes in irrigation rates (a), electricity costs (b), and crop yield (c) across the studied options of different levels of irrigation provision and typical groups of vegetation periods (illustrated with winter wheat irrigation) are summarized as follows: (a) *Irrigation Rates*: Variations in the amount of water applied under different irrigation regimes and vegetation periods. (b) *Electricity Costs*: Fluctuations in electricity expenditures related to water supply across different irrigation sufficiency levels and vegetation periods. (c) *Crop Yield*: Differences in crop yields resulting from varying irrigation levels and vegetation conditions. Source: the data from the study

periods (p = 50% – middle; p = 70% – dry; p = 90% – very dry), there is a more significant drop in winter wheat yields compared to other periods, given the same reduction in water and electricity costs. This pattern is consistent across all cultivated crops.

Table 3 provides generalized average weighted values for variables related to the resource-ecological (technological) effectiveness of irrigation. It compares various levels of irrigation provision for conditions corresponding to middle (p = 50%), dry (p = 70%), and very dry (p = 90%) vegetation periods, which require the highest water and electricity consumption. Crop yields are represented as productivity scores relative to the potential yield levels of the crops, facilitating comparative evaluation across different types of crops and yield characteristics.

Table 3. The generalized average weighted values for resource-ecological (technological) effectiveness of irrigation variables, based on the studied options for typical vegetation periods with the highest water and electricity consumption

Variable of resource-ecological (technological) effectiveness of irrigation and typical group of vegetation periods*		Option					
		control option	studied option No 1	studied option No 2	studied option No 3	studied option No 4	studied option No 5
costs of irrigation water ($m^3 \cdot ha^{-1}$)	p = 50%	1 722	1 263	1 208	1 154	1 076	907
	p = 70%	4 012	2 944	2 815	2 686	2 491	2 095
	p = 90%	6 698	4 913	4 698	4 482	4 155	3 495
costs of electricity ($kWh \cdot ha^{-1}$)	p = 50%	575	422	403	385	359	303
	p = 70%	1 340	983	940	897	832	700
	p = 90%	2 237	1 641	1 569	1 497	1 388	1 167
crop rotation productivity (points)	p = 50%	61	58	57	57	57	56
	p = 70%	63	54	52	51	49	46
	p = 90%	62	47	46	44	42	36

* (p = 50%) – middle, (p = 70%) – dry, and (p = 90%) – very dry vegetation periods.
Source: the data from the study

The study determined the values of resource-ecological (technological) effectiveness of irrigation indicators, averaged across the project crop rotation and typical vegetation periods. These averaged values were compared to the control option in percentage terms. The results of this comparative assessment are detailed in Table 4.

Table 4. The comparative assessment of the average weighted values of resource-ecological (technological) effectiveness of irrigation indicators for the study options, relative to the control option

Indicator of resource-ecological (technological) effectiveness of irrigation*	Option				
	studied option No 1	studied option No 2	studied option No 3	studied option No 4	studied option No 5
water and electricity consumption (%)	27.00	30.00	33.00	38.00	48.00
overall use of water and electricity resources (%)	24.00	26.00	29.00	33.00	43.00
crop rotation productivity (%)	10.80	11.75	13.31	14.32	18.06

* – data indicated in relation to the control option (change in value in percentage terms).
Source: the data from the study

This table illustrates how the effectiveness of different irrigation options measures up against the control, providing insights into the relative performance of various irrigation regimes in terms of resource efficiency and crop productivity.

In considering the implementation of the obtained results and selecting the best option, it is crucial to account for several factors in each specific case, including:

1. *Availability and Suitability of Resources*: Assess the availability of water and other resources necessary for irrigation, as well as their suitability for the chosen irrigation option.

2. *Investor and Land User Interests*: Consider the preferences and interests of investors and land users, ensuring that the selected option aligns with their goals and expectations.
3. *Financial Resources and Opportunities*: Evaluate the financial resources available and the opportunities for funding or investment, as these will influence the feasibility of implementing different options.
4. *Scale of Activity*: Take into account the scale of the agricultural activity or operation, as this will affect the choice of irrigation regime and its implementation.
5. *Strategic Importance*: Consider the strategic importance of the irrigation facility for the broader economy, including its role in regional or national agricultural productivity.
6. *Environmental Safety*: Ensure that the chosen option promotes environmental safety and sustainability, minimizing negative impacts on the environment.
7. *Other Critical Factors*: Address any additional factors specific to the facility that may influence the decision, such as regulatory requirements, technical feasibility, and long-term operational impacts.

These considerations will help in making a well-rounded decision that balances efficiency, sustainability, and practicality.

4. Conclusions

The research results demonstrate the technological efficiency of various irrigation regimes with different levels of water provision, revealing how reductions in water and electricity consumption impact crop rotation productivity. When water and electricity consumption decrease by 27% to 48%, there is a notable reduction in crop productivity—ranging from 10.80% to 18.06%. However, the overall use of water and electricity decreases by 24% to 43%. The final decision on reducing water and electricity consumption should be based on a thorough economic and investment evaluation of irrigation efficiency.

In the article, the research is carried out on the example of sprinkler irrigation, as the most common method of irrigation in Ukraine, but the proposed method is possible to perform the appropriate assessment of irrigation efficiency for justification of resource-saving solutions for other irrigation methods.

Given the current conditions and demands – such as climate change, and the increasing water, energy, and food crises – there is a clear need to adopt ecologically effective and nature-based solutions. This necessitates transforming how optimal project decisions are justified in constructing irrigation facilities, focusing on resource optimization. These solutions aim to address current challenges in irrigated agriculture while aligning with sustainable development principles. The goal is to ensure systematic, managed development that meets societal needs and safeguards future generations' interests.

Reducing water and electricity consumption in sprinkler irrigation is scientifically and practically justified for adapting irrigated agriculture to contemporary needs. The findings can support decisions that implement sustainable development concepts in crop production, especially in the face of global challenges such as climate change, water scarcity, food insecurity, and energy constraints.

5. Conflict of Interests

All authors confirm that they do not have any conflicts of interest.

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