ECOLOGICAL AND ECONOMIC OUTCOMES OF LONG-TERM IRRIGATION WITH MINERALIZED WATER

Iryna BIDNYNA[1], Raisa VOZHEHOVA[2], Liudmyla HRANOVSKA[2], Pavlo LYKHOVYD[2], Pavlo PYSARENKO[1], Valerii KOZYRIEV[2]

[1]Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine, Vasylkivska 37, Kyiv, Ukraine, E-mails: irinabidnian@ukr.net, iwpim.naan@gmail.com
[2]Institute of Climate-Smart Agriculture of the National Academy of Agrarian Sciences of Ukraine, Mayatskadoroha 24, vil. Khlibodarske, Odesa region, Ukraine, Phone: 380660629897; E-mails: icsanaas@ukr.net, G_Ludmila@ukr.net, pavel.likhovid@gmail.com, nwobhm@ukr.net

Corresponding author: pavel.likhovid@gmail.com

Abstract

Irrigation is essential for food security, but freshwater scarcity necessitates using mineralized water, which can degrade soil quality. This study analyzed the long-term effects of irrigating dark-chestnut soil in southern Ukraine with mineralized water from the Ingulets system and the economic impact. A stationary field experiment (1971–2020) assessed soil quality (cations, salts, sodicity) and water properties. Statistical analysis (Mann-Kendall, Sen's slope, ANOVA, regression, correlation) in Python 3 showed that Ingulets water (Class II, high mineralization) remained unsuitable for irrigation. Over time, irrigation increased sodification, toxic salts, and sodium while reducing calcium, harming soil structure and fertility. Fertilizers mitigated salinization in deeper layers and improved cation content. Economically, irrigation increased wheat yield by 0.82–1.66 t/ha, with pure additional profit of $206–$403/ha after deducting amelioration and fertilization costs. Despite soil risks, irrigation with mineralized water is economically viable in semi-arid regions, especially when combined with fertilizers and land reclamation practices.

Key words: *land degradation and reclamation, the Ingulets, mineralized water, economic efficiency*

INTRODUCTION

Current agriculture faces several serious challenges, which threaten sustainable crop production and food security, namely, global warming and consequent changes in climate patterns, and adverse effects of hostilities in Ukraine and Middle East [1]. Climate change resulted in dramatic shifts in air temperature on the annual scale and within the growing season, as well as disturbing usual regularities of rainfall distribution, air humidity, led to increased frequency of adverse meteorological events such as steep unpredictable shifts in temperatures, hailstorms, prolonged severe drought events, etc. All these changes arouse new difficulties for sustainable agricultural development, as well as aggravated the issues of natural resources use and environmental stability. Arid and semi-arid regions of the Earth are the most vulnerable to current climate change and related food insecurity issues [22].

Among the challenges, an important role belongs to freshwater resources availability for agricultural purposes. As far as it is known, agriculture is one of the biggest consumers of freshwater resources. Considering global climate aridization, the demand for irrigation to satisfy sufficient crop production and satisfy the needs of animal husbandry in arid and semi-arid zones will increase, simultaneously increasing the demand for freshwater in agriculture. General freshwater scarcity is one of the greatest issues for current agricultural science and practice [8]. On one hand, it will be almost impossible to deal with climate aggravation and related aridity issues to provide food security without proper irrigation. For this reason, researchers are looking for to solutions to help the farmers to maintain yields. For example, in Romania, there investigated crops, the average yields per hectare obtained under irrigated system were higher than those obtained under non-irrigated system [19].

In Egypt, it was studied the effect of water and fertilization levels on barley using different irrigation systems [3].

As for Ukraine, it was established that now nearly half of the country's territory requires irrigation to provide sustainable crop yields, and in the context of Kakhovka dam and reservoir destruction, the situation with national agricultural sector of economy in the South of the country, looks even more dramatic and threatening [13]. On the other hand, the water resources deficit calls for the development of resource-saving irrigation methods, as well as looking for alternative sources of water. In some cases, such sources include treated wastewater, collector and effluent waters, seawater, and other sources, which can provide sufficient volumes of water resources for irrigation but considering low water quality may pose risks of negative environmental impacts, especially on soils [7, 15]. These impacts include hazards of soil salinization, alkalization, sodicity increase, fertility loss, and general deterioration of soil health. Soil degradation prevention is an important task of modern ecology and agriculture, as far as normal life on the planet depends greatly on soil conditions [10]. To prevent soil quality deterioration, it is crucial to perform careful studies on possible negative consequences of irrigation with water of unfavorable quality on soil ecological and meliorative state. Apart from ecological threats, irrigation with low-quality water possesses economic disadvantages, as additional expenditures related to soil amelioration arise.

The main goal of this study was to establish the effects of continuous irrigation with mineralized water on the conditions of the dark-chestnut soil of the South of Ukraine and point out connected risks to environmental sustainability and evaluate whether there are any real economic benefits from applying irrigation with low-quality water through the calculation of real pure profits after irrigation application and consideration of land reclamation expenditures.

MATERIALS AND METHODS

The study was carried out at the irrigated and non-irrigated lands of the experimental fields of the Institute of Climate-Smart Agriculture of NAAS (former – the Institute of Irrigated Agriculture of NAAS), located in the Bilozersky district of Kherson region, Ukraine. The irrigated lands are of the Ingulets irrigation array. These lands are irrigated with the mineralized water from the Ingulets irrigation system, which nowadays is the main system, which supplies fields with water in Kherson and Mykolaiv regions of Ukraine. The water is polluted with the effluent disposals and wastes from the metallurgy industry; therefore, it is highly mineralized and saline [14].

To determine the peculiarities of elementary soil processes (ESP) in the dark-chestnut soil under the conditions of long-term irrigation with the Ingulets water, the study was carried out in a stationary experiment, which was established in 1971. Data from previous studies were used to determine changes in soil properties. The experiment is carried out with the following crop rotation: alfalfa (3 years old), winter wheat, grain corn, silage corn, winter wheat. The fertilizer rate is calculated for each crop in the crop rotation for the irrigated conditions (210 kg of NPK per hectare of crop rotation area). The sowing plot area was 240m^2. Crops cultivation technologies were generally accepted for the agroclimatic zone of the South of Ukraine. Mineral fertilizers (ammonium nitrate, superphosphate) were applied prior to the main tillage. The yields of wheat (as a reference crop for economic calculations) were estimated after complete harvesting of the experimental plots with self-propelled combine harvester. The yield of wheat grain was recalculated to standard moisture content in kernels (14%).

The water quality for irrigation by agronomic criteria was conducted with accordance to DSTU 2730:2015 [2013]. The analysis of the ionic and total dissolved solids (TDS, total and toxic salts) composition of the aqueous soil extract was performed by Hedroyts [8]; exchangeable sodium, calcium and magnesium contents were determined in an extract of 1% ammonium acetic acid using flame photometry [23]. Soil sodification was established with accordance to DSTU 3866-99 [20].

Statistical processing of the experimental data was performed in Python 3 within the IDE VS Code. Statistical procedures of Mann-Kendall and Sen's slope trend test at alpha=0.05, OLS linear regression analysis [2], correlation matrix analysis [17], heatmap analysis [5] were performed. The standard deviation (SD) and coefficient of variation (CV) were calculated and interpreted with accordance with common international guidelines [18]. Economic outcomes were estimated for winter wheat reference crop through the calculation of grain yield price, additional yield price received at the expense of irrigation and fertilizers, and the difference between the variants. The price of amelioration measures to restore soil conditions in terms of salt content in the 0-30 cm layer was calculated assuming the application of phosphogypsum for this purpose. Water costs for irrigation and costs for fertilizers application were also accounted for. All the prices were paid as of February 4th, 2025.

RESULTS AND DISCUSSIONS

Table 1 provides a detailed analysis of the quality of Ingulets irrigation water from 2001 to 2020, with key findings summarized as follows. The average TDS content was 1.531 g/L, with relatively low variability (CV = 4.35%). The values remained consistent over the years, indicating stable salinity levels, which are marginally suitable for irrigation. The mean pH was slightly alkaline at 8.1, with minimal fluctuation (CV = 2.61%). This aligns with typical irrigation water requirements, posing no significant risk to soil fertility and structure. Toxic concentrations were expressed in chloride equivalents and averaged to 14.3 meq/L with a CV of 16.70%, suggesting moderate variability. These levels generally fall within acceptable ranges for irrigation purposes but may pose some harm to susceptible plants. The average sodium percentage was 52.72%, with low variability (CV = 7.41%). While consistent, high sodium levels could potentially contribute to soil sodification and related hazards if not managed properly. The magnesium and calcium ion content averaged to 1.95 meq/L (CV = 18.34%) and 0.34 meq/L (CV = 20.02%), respectively. These levels reflect a balanced ionic composition that supports soil structure. The mean concentrations of carbonates, bicarbonates, and chlorides were 0.11 meq/L, 2.4 meq/L, and 10.45 meq/L, respectively, with bicarbonates and chlorides showing moderate variability. The low carbonate content indicates minimal alkalinity risk. As for hazard assessments, the Ingulets irrigation water was classified as "Class II" (moderate risk) throughout the study period, as it possesses occasional risks of alkalization and toxicity that require appropriate ameliorative monitoring and management.As for the tendencies in the Ingulets irrigation water quality, it was established that there is no significant trend to change for most quality indicators. Bicarbonates content was the only indicator with reliable trend to increase, talking about potential increase in alkalization hazards and toxicity of the studied water for soil and agricultural plants (Table 2).

As for soil sodium content analysis, following regularities were established across the studied options. In the variant 'No Irrigation, Without Fertilizers' sodium levels ranged from 0.27 to 0.39 meq/100 g, averaging to 0.32 meq/100 g. The sodification level remained consistently classified as "slight" over the years, indicating minimal impact on soil salinity in this variant. As for the variant 'Irrigation, Without Fertilizers', sodium content varied between 0.45 and 0.65 meq/100 g, with an average of approximately 0.56 meq/100 g. The sodification level was predominantly "moderate," reflecting increased sodium accumulation due to irrigation without the mitigating effects of fertilizers. The same was true for the variant 'Irrigation Plus Fertilizers', where sodium levels ranged from 0.40 to 0.65 meq/100 g, with an average around 0.54 meq/100 g. Thus, the application of fertilizers did not significantly alter sodification traits (Table 3).

Table 1. Quality of the Ingulets irrigation water during 2001-2020 assessed by agronomic criteria, evaluated with accordance to DSTU 2730:2015

Year	TDS content, g/L	pH	Toxic ions in eCl^-, meq/L	Sodium percentage, %	$\frac{Mg^{2+}}{Ca^{2+}}$	$\frac{Ca^{2+}}{Na^+}$	Anions content, meq/L			Water quality for irrigation according to DSTU 2730:2015			
							CO_3^{2-}	HCO_3^-	Cl^-	Salinization hazard	Sodification hazard	Alkalization hazard	Toxic effects hazard
2001	1.492	8.2	11.8	50.9	1.8	0.3	0.1	2.2	9.7	II	II	II	II
2002	1.539	7.8	12.4	57.4	1.9	0.3	0	2.1	9.8	II	II	II	II
2003	1.547	8.1	13.3	58.3	2.0	0.4	0.1	1.6	10.9	II	II	III	III
2004	1.473	8.0	16.4	51.0	1.6	0.3	0.1	2.0	9.2	II	II	II	II
2005	1.528	8.5	13.4	49.8	1.9	0.3	0	1.8	10.9	II	II	II	II
2006	1.425	8.6	14.6	54.8	1.8	0.3	0.2	2.6	9.4	II	II	II	III
2007	1.462	8.3	18.2	51.6	1.8	0.4	0.1	2.3	6.9	II	II	II	II
2008	1.580	8.2	20.1	63.7	1.8	0.2	1.2	2.9	10.3	II	II	II	II
2009	1.526	8.0	13.1	50.0	2.1	0.3	0	2.8	11.1	II	II	III	III
2010	1.436	8.1	14.1	50.1	2.1	0.3	0	2.3	11.6	II	II	II	II
2011	1.522	8.3	18.9	54.4	3.1	0.3	0.1	1.2	12.5	II	II	II	II
2012	1.599	7.9	14.1	49.0	2.6	0.3	0	1.1	12.0	II	II	II	II
2013	1.528	8.1	11.4	51.8	1.6	0.5	0	3.2	9.2	II	II	II	II
2014	1.565	8.3	13.8	58.2	1.8	0.4	0.1	3.2	10.2	II	II	II	II
2015	1.633	8.0	13.7	49.7	2.2	0.3	0	2.1	11.6	II	II	II	II
2016	1.596	8.2	15.5	51.2	1.9	0.3	0.2	3.0	10.3	II	II	II	II
2017	1.432	7.8	11.5	49.6	1.8	0.4	0	2.9	9.5	II	II	II	II
2018	1.661	7.9	13.4	49.6	1.7	0.4	0	3.6	11.0	II	II	II	II
2019	1.581	8.1	14.0	51.0	1.9	0.3	0	2.6	11.7	II	II	II	II
2020	1.489	8.0	12.9	52.2	1.6	0.4	0	3.0	11.1	II	II	II	II
mean	1.531	8.1	14.3	52.72	1.95	0.34	0.11	2.4	10.45				
SD	0.07	0.21	2.39	3.91	0.36	0.07	0.27	0.68	1.28				
CV, %	4.35	2.61	16.70	7.41	18.34	20.02	241.25	27.90	12.27				

Source: [14].

Table 2. Mann-Kendall and Sen's slope test (alpha = 0.05) for the Ingulets irrigation water quality indicators for 2001-2020

Statistics	TDS, g/L	pH	eCl^-, meq/L	Sodium percentage, %	$\frac{Mg^{2+}}{Ca^{2+}}$	$\frac{Ca^{2+}}{Na^+}$	CO_3^{2-}	HCO_3^-	Cl^-
Mann-Kendall test									
MK-stat	43	-38	-6	-38	-9	37	-41	70	53
SD	30.805	30.386	30.789	30.789	30.139	26.627	27.489	30.724	30.741
Z-stat	1.363	-1.218	-0.162	-1.202	-0.265	1.352	-1.455	2.246	1.692
P	0.173	0.223	0.871	0.229	0.791	0.176	0.146	0.025	0.091
trend	no	no	no	no	no	no	no	yes	No
Sen's slope test									
slope	0.005	-0.011	-0.016	-0.083	0	0	0	0.061	0.073
lower	-0.002	-0.033	-0.160	-0.456	-0.020	0	-0.008	0.008	-0.017
upper	0.010	0.006	0.122	0.068	0.017	0.006	0	0.100	0.186

Source: Own results.

Table 3. Long-term changes in sodium content in the soil depending on irrigation and fertilizers application with accordance to DSTU 3866-99

Year	Variant					
	No irrigation, without fertilizers		Irrigation, without fertilizers		Irrigation plus fertilizers	
	Na^+ meq/ 100 g	Sodification level	Na^+ meq/ 100 g	Sodification level	Na^+ meq/ 100 g	Sodification level
2001	0.30	Slight	0.65	moderate	0.65	moderate
2002	0.27	Slight	0.53	moderate	0.49	moderate
2003	0.32	Slight	0.58	moderate	0.57	moderate
2004	0.29	Slight	0.53	moderate	0.48	moderate
2005	0.28	Slight	0.55	moderate	0.51	moderate
2006	0.30	Slight	0.50	moderate	0.45	moderate
2007	0.30	Slight	0.45	moderate	0.40	moderate
2008	0.30	Slight	0.50	slight	0.65	slight
2009	0.28	Slight	0.65	moderate	0.46	slight
2010	0.30	Slight	0.56	moderate	0.47	moderate
2011	0.35	Slight	0.58	moderate	0.48	moderate
2012	0.31	Slight	0.57	moderate	0.52	moderate
2013	0.36	Slight	0.52	moderate	0.59	moderate
2014	0.32	Slight	0.59	moderate	0.46	moderate
2015	0.35	Slight	0.58	moderate	0.48	moderate
2016	0.36	Slight	0.61	moderate	0.56	moderate
2017	0.34	Slight	0.56	moderate	0.64	moderate
2018	0.39	Slight	0.49	moderate	0.57	moderate
2019	0.35	Slight	0.57	moderate	0.63	moderate
2020	0.38	Slight	0.61	moderate	0.54	moderate

Source: Own results.

Trend analysis showed no significant sodification in irrigated soils, while rainfed soils exhibited increasing sodification. In semi-arid conditions, lack of irrigation prevents sodium leaching, leading to accumulation. Thus, irrigation helps reduce sodification by flushing excess sodium from the arable layer (Table 4).

Table 4. Mann-Kendall and Sen's slope test (alpha = 0.05) for the sodium content in the studied soil within the period 2001-2020

Statistics	No irrigation, without fertilizers	Irrigation, without fertilizers	Irrigation plus fertilizers
Mann-Kendall test			
MK-stat	116	21	28
SD	30.441	30.665	30.714
Z-stat	3.778	0.652	0.879
P	0.0001	0.514	0.379
trend	yes	no	no
Sen's slope test			
slope	0.005	0.002	0.004
lower	0.003	-0.004	-0.004
upper	0.006	0.005	0.010

Source: Own results.

As for salts content in the soil, it was established that there are some differences across the variants of the study in their distribution over the layers and accumulation patterns (Table 5). In the variant 'No Irrigation, Without Fertilizers' the total salt content in the 0–30 cm layer decreased slightly over time, from 2.949 t/ha (2001) to 2.231 t/ha (2020); in the 0–100 cm layer, the total salt content remained relatively stable, around 12.3 t/ha by 2020. Toxic salt content decreased marginally in both layers, with a more pronounced decline in the 0–30 cm layer (from 1.470 t/ha in 2001 to 1.282 t/ha in 2020). In the variant 'Irrigation, Without Fertilizers' the total salt content in the 0–30 cm layer decreased over time, from 3.920 t/ha (2001) to 2.961 t/ha (2020). In the 0–100 cm layer, total salt content reduced slightly from 16.848 t/ha (2001) to 13.228 t/ha (2020). Toxic salt content in the 0–30 cm layer also declined, from 2.850 t/ha (2001) to 2.467 t/ha (2020). However, the toxic salt content in the deeper 0–100 cm layer showed fluctuations, ending at 10.656 t/ha in 2020. As for the variant 'Irrigation Plus Fertilizers', the total salt content in the 0–30 cm layer slightly increased, from 4.004 t/ha (2001) to 3.504 t/ha

(2020). In the 0–100 cm layer, total salt content decreased slightly, from 15.268 t/ha (2001) to 14.548 t/ha (2020). Toxic salt content in the 0–30 cm layer fluctuated, remaining almost similar by 2020 (2.540 t/ha). In the deeper 0–100 cm layer, toxic salt content showed a notable decrease, from 10.510 t/ha (2001) to 8.494 t/ha (2020). As for the temporal changes, differences were also observed among the studied variants. Thus, in the variant 'No Irrigation, Without Fertilizers' salt content showed a gradual decline over two decades, particularly in the arable layer (0–30 cm), indicating natural leaching or stabilization over time. In the variant 'Irrigation, Without Fertilizers' both total and toxic salt contents decreased over time, especially in the arable layer (0–30 cm), suggesting the partial leaching effect of irrigation water. However, toxic salt content remained higher in deeper layers (0–100 cm), indicating possible accumulation in subsurface soil layers due to the mentioned above leaching. This may improve the growth of agricultural plants with shallow and moderately deep root systems but will have adverse effects on the plants with deep root systems. In the variant 'Irrigation Plus Fertilizers' the arable layer (0–30 cm) showed relatively stable toxic salt content, while the deeper layer (0–100 cm) experienced a decline in toxic salts content over time. Total salt content exhibited weak reductions, indicating some mitigation of salinity risks through fertilizer use.

To sum up, non-irrigated soil maintained the lowest salt content overall, confirming minimal salinization risks in the absence of irrigation with mineralized water. Irrigation without fertilizers application resulted in higher salt accumulation through the whole soil profile compared to non-irrigated soil, though reductions were observed over time due to partial leaching. Irrigation with fertilizers usage showed slight increases in arable layer salt content but notable reductions in toxic salts in the deeper layer, suggesting fertilizers may help mitigate long-term salinization.

Table 5. Effect of long-term irrigation and fertilizers on salt content in the studied soil

Year	Soil layer, cm	Salt content, t/ha	
		total	toxic
No irrigation, without fertilizers			
2001	0-30	2.949	1.470
	0-100	12.740	7.140
2006	0-30	2.574	1.148
	0-100	11.900	6.300
2010	0-30	2.306	1.319
	0-100	12.320	7.140
2015	0-30	2.416	1.386
	0-100	12.180	7.000
2020	0-30	2.231	1.282
	0-100	12.320	6.860
Irrigation, without fertilizers			
2001	0-30	3.920	2.850
	0-100	16.848	12.700
2006	0-30	3.192	2.184
	0-100	15.600	10.650
2010	0-30	3.044	2.169
	0-100	13.228	9.634
2015	0-30	3.066	2.100
	0-100	14.400	9.750
2020	0-30	2.961	2.467
	0-100	13.228	10.656
Irrigation plus fertilizers			
2001	0-30	4.004	2.540
	0-100	15.268	10.510
2006	0-30	3.182	1.958
	0-100	14.544	9.072
2010	0-30	3.253	2.457
	0-100	13.972	9.646
2015	0-30	3.345	2.448
	0-100	14.256	9.648
2020	0-30	3.504	2.540
	0-100	14.548	8.494

Source: Own results.

Both regression models for total and toxic salt content in the soil provided great fit quality and high accuracy. The model for total salts content is more accurate and fits the data somewhat better than the model for toxic salts, as evidenced by higher R^2, adjusted R^2, and better AIC/BIC scores. Both models are statistically significant, with negligible p-values indicating strong relationships between predictors and outcomes, testifying that the inputs are decisive for the output formation, and almost no external effects are present. While both models are robust, the model for total salts content shows a stronger association with the inputs compared to the model for toxic salts content. Lower AIC and BIC values for the model of total salts suggest that this model is more efficient in balancing complexity and accuracy (Table 6).

Table 6. Regression statistics for the total and toxic salts content in the studied soil

Statistical indicator	Total salts	Toxic salts
R^2	0.982	0.922
Adjusted R^2	0.980	0.913
F-statistics	472.6	102.1
Prob (F-statistics)	8.70×10^{-23}	1.66×10^{-14}
Log-likelihood	-33.351	-43.839
AIC	74.70	95.68
BIC	80.31	101.30

Source: Own results.

Detailed regression statistics and model parameters are provided in Table 7. According to the t and P values, the greatest impact on salts content is associated with irrigation treatment. Soil depth plays a secondary role, while the time span is the least important influential factor. It must be stressed that the negative values of the 'Year' coefficient testifies about slight tendency to salt content decrease over the years, while the highest value of the coefficient for 'Irrigation' input suggests that irrigation is the main driving force to salinization hazards.

The effect of long-term irrigation and fertilizers on the cations' ratio and content in the studied soil is presented in Table 8.The correlation matrix for the main cations in the studied soil is provided on Fig. 1.

Table 7. Regression models and their statistical evaluation for the total and toxic salts content in the studied soil

	coefficient	SD	t	P > |t|	0.025	0.975
Total salts model						
Intercept	104.6178	43.598	2.400	0.024	15.001	194.234
Year	-0.0532	0.022	-2.453	0.021	-0.098	-0.009
Soil depth, cm	0.1537	0.004	37.301	0	0.145	0.162
Irrigation	0.7970	0.177	4.512	0	0.434	1.160
Toxic salts model						
Intercept	61.2697	61.844	0.991	0.331	-65.852	188.392
Year	-0.0314	0.031	-1.021	0.317	-0.095	0.032
Soil depth, cm	0.0999	0.006	17.087	0	0.088	0.112
Irrigation	0.9134	0.251	3.645	0.001	0.398	1.428

Source: Own results.

Table 8. Effect of long-term irrigation and fertilizers on the cations' ratio and content in the studied soil

Variant	Year of the study, period	Soil layer, cm	Cations content, meq/100 g			Total exchangeable cations content, meq/100 g	Share, %		
			Ca^{2+}	Mg^{2+}	Na^{+}		Ca^{2+}	Mg^{2+}	Na^{+}
No irrigation, without fertilizers	2001 (31 years)	0-30	13.8	4.8	0.30	18.90	73.02	25.40	1.59
	2006 (36 years)	0-30	13.2	4.8	0.30	18.30	72.13	26.23	1.64
	2010 (40 years)	0-30	12.4	4.6	0.30	17.30	71.68	26.59	1.73
	2015 (45 years)	0-30	12.2	4.6	0.35	17.15	71.14	26.82	2.04
	2020 (50 years)	0-30	12.5	4.7	0.38	17.58	71.10	26.73	2.16
Irrigation, without fertilizers	2001 (31 years)	0-30	11.8	5.6	0.65	18.05	65.37	31.02	3.60
	2006 (36 years)	0-30	12.0	5.2	0.50	17.70	67.80	29.38	2.82
	2010 (40 years)	0-30	12.0	5.4	0.56	17.96	66.82	30.07	3.12
	2015 (45 years)	0-30	11.9	5.5	0.58	17.98	66.18	30.59	3.23
	2020 (50 years)	0-30	12.3	6.0	0.61	18.91	65.04	31.73	3.23
Irrigation plus fertilizers	2001 (31 years)	0-30	12.2	5.2	0.65	18.05	67.59	28.81	3.60
	2006 (36 years)	0-30	12.4	4.8	0.45	17.65	70.25	27.20	2.55
	2010 (40 years)	0-30	12.2	5.4	0.47	18.07	67.52	29.88	2.60
	2015 (45 years)	0-30	12.1	5.3	0.48	17.88	67.67	29.64	2.68
	2020 (50 years)	0-30	12.4	5.9	0.54	18.80	65.85	31.28	2.87

Source: Own results.

There is a strong correlation between magnesium and sodium content (R=0.81), suggesting a cumulative effect of these ions, likely from irrigation. Both ions are antagonistic to calcium [21], with moderate negative correlation for magnesium (R=-0.44) and stronger for sodium (R=-0.69), supporting the idea that sodium displaces calcium and affects soil structure. Magnesium also exacerbates sodium's harmful effects.

Heatmaps of cation content show that non-irrigated soils have the highest calcium (71-

73%), while irrigated soils have lower calcium (65-70%), with higher levels in 2006 for irrigated and 2001 for non-irrigated soils. Magnesium content is lowest in rainfed soil (25-27%) and highest in irrigated soils (27-32%), with peak values in 2020.

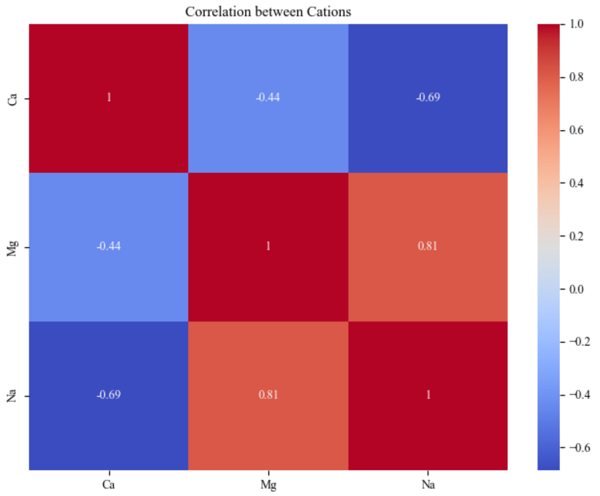

Fig. 1. Correlation matrix for cations content in the studied soil
Source: Own results.

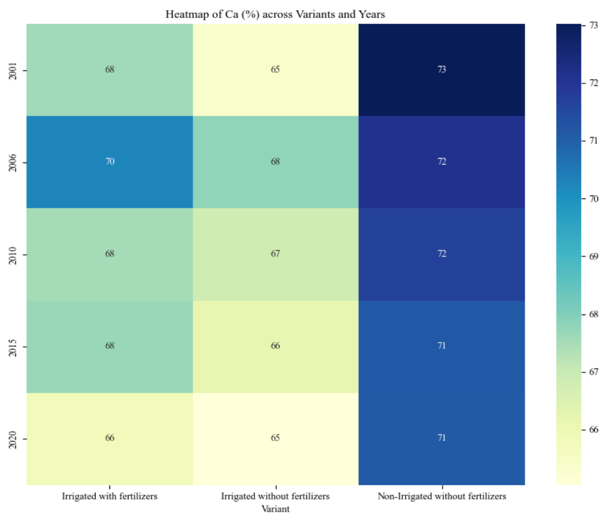

Fig. 2. Heatmap of Ca^{2+} cations across the variants and years of the study
Source: Own results.

Sodium content is lowest in non-irrigated soils (1.6-2.2%) and highest in irrigated soils (2.5-3.6%), particularly in 2001, indicating that irrigation contributes significantly to soil alkalization and sodification, with fertilizers offering some detoxification effect. These findings align with the view that irrigation is a major cause of soil salinity and sodicity, while organic fertilizers also improve soil health [16]. The fact that not only chemical amelioration agents such as gypsum are efficient in soil sodification management, but fertilizers, especially organic ones, play a crucial role in soil health improvement is also supported by some scientists [11].

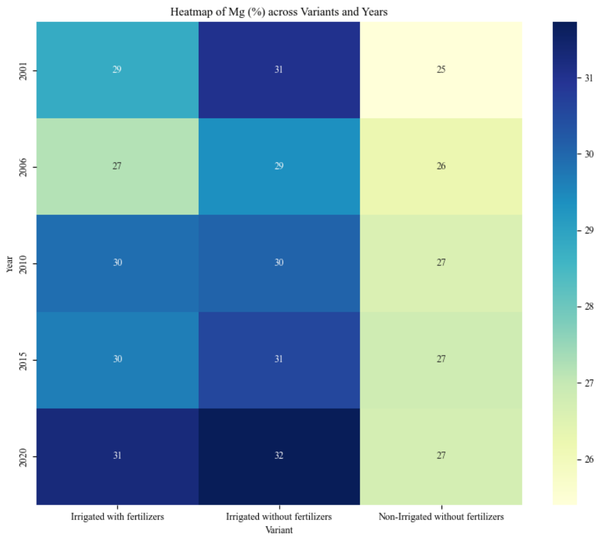

Fig. 3. Heatmap of Mg^{2+} cations across the variants and years of the study
Source: Own results.

Fig. 4. Heatmap of Na^{+} cations across the variants and years of the study
Source: Own results.

Over the years, the yield of winter wheat declines in the absence of irrigation, leading to lower income per hectare (Table 9). Conversely, irrigation – both with and without fertilizers – substantially improves yield, increases revenue, and enhances economic efficiency. The application of phosphogypsum was required (0.618–1.25 t/ha) to manage salt accumulation due to mineralized water irrigation. After deducting amelioration, irrigation, and fertilization costs, the pure additional profit ranged from $66 to $269 per hectare. Fertilizers were the most powerful factor of yield increase and economic efficiency rise. Irrigation alone increased profits, but irrigation with fertilizers yielded 2 to 3 times higher net economic returns.

Table 9. Economic evaluation of the irrigation with mineralized water and fertilizers application for the reference crop – winter wheat

Year	Winter wheat yield, t/ha	Yield price, USD/ha	Additional profit, USD/ha	Salts to be removed, t/ha	Phosphogypsum needed, t/ha	Amelioration, irrigation, and fertilization price, USD/ha	Pure additional profit, USD/ha
No irrigation, without fertilizers							
2001	2.66	644	-	-	-	-	-
2006	2.30	557	-	-	-	-	-
2010	2.59	627	-	-	-	-	-
2015	2.35	570	-	-	-	-	-
2020	2.18	529	-	-	-	-	-
Irrigation, without fertilizers							
2001	3.51	850	206	0.971	1.25	140	66
2006	3.56	864	307	0.618	0.80	132	175
2010	3.89	942	315	0.738	0.95	134	180
2015	3.61	876	307	0.650	0.84	132	174
2020	3.84	932	403	0.730	0.94	134	269
Irrigation plus fertilizers							
2001	5.40	1310	666	1.055	1.36	142	524
2006	4.48	1087	530	0.608	0.79	131	399
2010	4.71	1141	513	0.947	1.22	139	374
2015	5.41	1312	742	0.929	1.20	139	603
2020	5.32	1290	761	1.273	1.64	147	614

Source: Own results.

In general, our study provides additional proof and valuable insights about adverse effects of irrigation with mineralized water on soil health. Its main advantage is a long-term nature, as well as comprehensive statistical evaluation of the results. It agrees with the works on long-term effects of saline water irrigation on microbial activity and carbon storage in soils [25]; the study of the adverse effects of mineralized water on soil salinity and yield reduction of cotton plants in China [4]. Another study highlights the susceptibility of finer-textured, clay-rich soils of Egypt to structural degradation under the impact of irrigation with water containing high TDS and sodium [6]. To sum up, soil quality and health deterioration, connected with mineralized water irrigation and consequent soil salinization, alkalization and sodification, results in great environmental hazards and reduces productivity of agricultural ecosystems, threatening global food security [12]. As for the economic outcomes, foreign studies also support the need for irrigation in semi-arid regions regardless of water quality, because irrigation in such cases is the only factor which can dramatically improve crops productivity and provide for food security and sustainable agriculture [24].

CONCLUSIONS

Irrigation with mineralized water risks soil degradation and requires careful monitoring. It leads to gradual salt accumulation (0–30 cm, 0–100 cm) and shifts cation balance toward magnesium and sodium. These statistically significant changes must be considered in irrigation planning. Fertilizers help mitigate soil degradation but do not prevent long-term harm. Continuous irrigation with poor-quality water necessitates land reclamation and chemical amelioration. Economically, it increases yield (0.82–1.66 t/ha) and profitability, with phosphogypsum costs outweighed by higher net profit. Despite soil risks, it remains a viable strategy for sustainable agriculture in water-scarce regions.

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