agronomy

MDPI

Article

Low-Cost Smart Farm Irrigation Systems in Kherson Province: Feasibility Study

Oleg Bazaluk [1], Valerii Havrysh [2], Vitalii Nitsenko [3,*], Yuliia Mazur [4] and Sergiy Lavrenko [5]

[1] Belt and Road Initiative Institute for Chinese-European Studies, Guangdong University of Petrochemical Technology, Maoming 525000, China; bazaluk@ukr.net
[2] Department of Tractors and Agricultural Machinery, Operating and Maintenance, Mykolayiv National Agrarian University, 54020 Mykolaiv, Ukraine; havryshvi@mnau.edu.ua
[3] SCIRE Foundation, 00867 Warsaw, Poland
[4] Educational and Scientific Institute of Management, Economics and Finance, Interregional Academy of Personnel Management, 03039 Kiev, Ukraine; gy__89@ukr.net
[5] Department of Agriculture, Kherson State Agrarian and Economic University, 73006 Kherson, Ukraine; lavrenko.sr@gmail.com
* Correspondence: vitaliinitsenko@onu.edu.ua; Tel.: +380-939983073

Abstract: The growth of the world population requires an increase in food production. Its solution requires the introduction of advanced technologies, including automated irrigation systems. Commercially available smart irrigation systems are not widespread because of their high cost. A low-cost smart irrigation system based on satellite monitoring is proposed to schedule irrigation. The purpose of this study was to investigate the smart irrigation system during five-year field experiments. Water-use productivity, irrigated water-use productivity, and payback period were used as indicators to evaluate the low-cost irrigation system. This study was carried out for four crops: wheat, corn, sunflower, and rapeseed. The results obtained were compared to conventional irrigation systems. The experiments were designed at five farms locations. Their results showed that average water-use productivity rose from 4.09% (wheat) to 9.8% (sunflower). An increase in yields varied from 5.72% (wheat) to 13.42% (corn). Corn had a maximum yield deviation (26.72%). The payback period depended on the crop variety and the plot area. The payback period for wheat production under the proposed system was the longest (up to 82 months). Payback periods for corn, sunflower, and rapeseed production were shorter (from 3 to 12 months). Therefore, the smart irrigation system provides advantages and can be recommended as a low-cost solution.

Keywords: smart irrigation; water-use productivity; yield; irrigation strategy

check for updates

Citation: Bazaluk, O.; Havrysh, V.; Nitsenko, V.; Mazur, Y.; Lavrenko, S. Low-Cost Smart Farm Irrigation Systems in Kherson Province: Feasibility Study. *Agronomy* **2022**, *12*, 1013. https://doi.org/10.3390/agronomy12051013

Academic Editors: Jesús Montero Martínez and Angel Martínez Romero

Received: 20 March 2022
Accepted: 21 April 2022
Published: 23 April 2022

1. Introduction

The increase of the world population [1] requires an increase in food production. It is a challenge for agriculture. It must use innovative technologies to improve the efficiency of all production processes, including irrigation systems. Despite the relatively limited irrigation areas, irrigation agriculture is expected to produce a significant quantity of food [1,2]. Water is a vital resource for agriculture. It impacts the social and economic life of any country. The agriculture of some countries largely depends on irrigation [3]. Farmers need innovative irrigation technologies for their sustainable development. Moreover, due to global climate change, the climate is becoming more arid. Agriculture is the most sensitive sector of the economy to climate change. Droughts result in a decrease in yields and the profitability of agriculture. In general, climate change increases risks for sustainable crop production. Due to climate change, arid areas are expanding. This phenomenon hinders food production [4]. For this reason, farmers are forced to develop irrigation systems to overcome water scarcity.

The world's arable land is decreasing because of climate change, soil erosion, etc. India has the most arable land, consisting of 156.5 million hectares. India is followed by the USA

(152.3 million hectares) and Russia (123.1 million hectares). China has the fourth largest amount of agricultural land in the world (118.9 million hectares). Ukraine has 32.8 million hectares of arable land. It is in the tenth position in the world [5].

The lack of precipitation forces farmers to use irrigated agriculture. There are currently 324 million hectares of irrigated land in the world. Bangladesh is the leader in the relative area of irrigated land. Its share of irrigated land is 59.71%. China is ranked thirtieth (10.49%) and Ukraine is ranked ninety first (0.79%) [6]. Due to climate change, in Ukraine, only 11.30% of the arable land does not require irrigation [7]. Ukrainian farmers are forced to expand irrigation and use resource-saving technologies to overcome current climate change.

Fresh water availability for agricultural irrigated land varies between countries and their regions. Ukraine is situated in the Eastern European region. In this region, internal renewable water resources (IRWR) per inhabitant range from 227 m^3/year (the Republic of Moldova) to 29,000 m^3/year in the Russian Federation. Ukraine depends on other countries for 62% for their renewable water resources. IRWR per habitant for China is 2245 m^3/year. Its dependency ratio is 0.6% [8].

Agriculture consumes around 70% of total water in the world [9]. Under these conditions, water management gains particular importance. Modern practices can lead to over-irrigation. Many farmers use a fixed irrigation cycle. This cycle uses a fixed amount of water. In most cases, it results in over-irrigation. This increases specific energy, water, fertilizer, and labor use, while yields and economic profitability decrease [10]. For this reason, the authorities of many countries are developing strategies to improve the sustainability of food production, paying attention to water management [10–14].

The limitations of water resources and the deterioration of quality results can be seen in an increase in the number of studies focused on irrigation systems and their processes [13–16]. These are reasons for the implementation of technological innovations. These technologies may be rather expensive. Initial investment costs of a smart irrigation system can be up to EUR500/ha higher than a conventional irrigation system [17,18].

As a rule, farmers use their own experience to develop irrigation scheduling [19]. An optimized irrigation strategy requires taking into account many factors, such as weather conditions, soil quality, crop species, irrigation system, etc. [20]. The application of this strategy needs the irrigation systems to be equipped with digital tools to make decisions for automatic control [21–25].

Smart irrigation can optimize crop production and reduce the consumption of different resources, including water and energy. It establishes a proper amount of water supply and timing [26]. As a result, farmers obtain the maximum yields and reduce operational costs. Researchers pay a lot of attention to smart irrigation systems. Abrishambaf et al. [27] studied irrigation scheduling based on energy and water supply optimization. Dong et al. [28] analyzed an irrigation model for a central pivot irrigation system based on a wireless sensor network. An automatic irrigation system based on the internet of things (IoT), a microcontroller, and a cloud server was developed by Boobalan et al. [29] and Pernapati [30]. Optimization of operational costs and development of smart software are in the spotlight too [31]. Semantic data modeling is used in smart irrigation systems. These models estimate a number of parameters, such as soil type, water requirement, etc. Based on real-time sensors reading, the software controls the irrigation processes [32].

However, most of the innovative solutions for smart irrigation are not practically available for commercial application. Commercially available systems are expensive for use in developing countries and by small farmers. Therefore, there is an urgent need to develop low-cost smart irrigation systems. We put forward the following hypothesis: the low-cost Rain-1 module (developed in Ukraine) can convert a conventional irrigation system into a smart one and improve its water-use efficiency.

This article aims to assess the effectiveness of the low-cost smart irrigation system. To achieve this aim, we set up three goals:

- To investigate climate conditions.
- To study water-use productivity.

- To estimate the payback period of a retrofitted irrigation system.

2. Materials and Methods

This study focuses on the assessment of a retrofitted irrigation system. We studied a retrofitted center pivot irrigation system (CPIS) for five years. This study assessed the impact of a low-cost irrigation system on water-use productivity and economic indicators, such as the payback period and an increase in income. The study combined field experiments and the mathematical analysis of obtained data. Our methodology comprises the following stages: the collection of field experiment data; the determining of the water-use productivity; the determining of the irrigated water-use productivity; the calculation of additional income; and the assessment of the payback period for a low-cost smart irrigation system.

2.1. Climate

The climate of the Kherson province is temperate–continental. It has relatively mild winters and hot summers. The average annual air temperature ranges from 9.8 to 10.8 °C. This has been the average long-term air temperature for the last 30 years. The annual rainfall varies from 239 to 969 mm per year. Its average value is 444 mm. About 65% of precipitation falls in the warm season. Kherson province is the driest region of Ukraine. The climate is characterized by dry winds (speed is higher than 5 m/s), low humidity (less than 30%), and air temperatures above 25 °C. Such climatic conditions impede obtaining high yields. The monthly rainfall and air temperatures during the study are presented in Figure 1 [33].

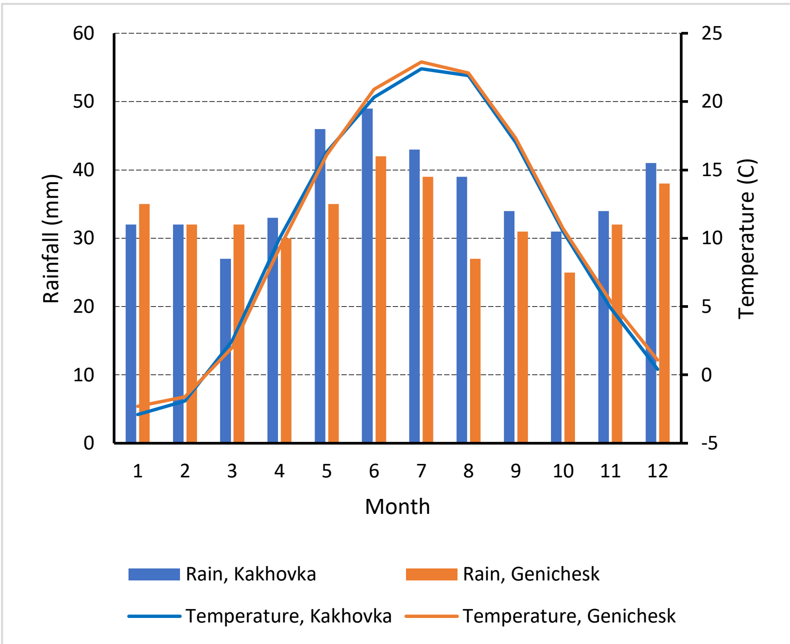


Figure 1. Average temperatures and rainfall (during the five years of experiments).

2.2. Irrigation Water Supply

Irrigation water is delivered from the nearby North Crimean irrigation canal. Irrigation water quality is assessed by standard methods [9,34,35]. Its pH is equal to 8.3. The water contains soluble salts and compounds as follows: hydrocarbonates—68.40 mg/L, sulphates—82.00 mg/L, chlorides—40.80 mg/L, calcium—44.20 mg/L, magnesium—24.30 mg/L, sodium—32.90 mg/L, and ammonia nitrogen—0.15 mg/L.

2.3. Field Experiments

Field experiments were carried out for the following crops: winter rapeseed, winter wheat, corn, and sunflower. Five farms took part in this study. They are located in the Henichesk and Kakhovka districts of Kherson province (southern Ukraine) (Figure 2). Their geographic coordinates are as follows: 46°33′22″ N and 34°08′25″ E; 46°31′05″ N and 34°17′23″ E; 46°38′16″ N and 32°27′59″ E; 46°26′48″ N and 33°41′53″ E; 46°39′00″ N and 33°34′35″ E. The Kherson province is a dry steppe. The soils of the farms are dark chestnut, deflated soils. Soil properties are presented in Table 1. Groundwater depth was more than 5 m and water infiltration was 1.3–2.2 mm/min. Crops were cultivated by conventional agricultural practices (Table 2).

Figure 2. Districts of the Kherson province.

Table 1. Primary soil properties.

Indicators	Unit	Farm				
		1	2	3	4	5
Soil organic carbon	g·kg^{-1}	2.3	2.4	2.8	2.5	2.3
pH	-	8.1	8.1	6.8	7.1	5.0
Nitrogen	mg·kg^{-1}	35	25	24	34	31
Phosphorus	mg·kg^{-1}	32	31	34	30	37
Potassium	mg·kg^{-1}	298	310	500	412	546
Bulk density	kg·m^{-3}	1380	1390	1370	1365	1374

The farmers use crop rotation. They grow the same crop in a plot with the following intervals: wheat—from 1 to 3 years; corn—from 0 to 5 years; sunflower—from 5 to 9 years; and rapeseed—from 4 to 5 years.

There were two CPIS for each crop: control and experimental. The experimental CPIS was retrofitted CPIS. The irrigated area of each CPIS was 41 hectares. It was equipped with a tracker and a computer. This CPIS obtained information through a satellite concerning soil moisture and plant conditions. A weather station was used to obtain air temperature, wind, and precipitation data. The computer processed the above information and controlled water consumption. It used an original program. Conventional irrigation systems rely on an operator's experience. They use simple parameters, such as the crop types, season, and available water. We compared two different irrigation strategies by the number of indicators, such as yield, water-use productivity, and financial costs.

Table 2. Agricultural practices.

Farming Operation	Crop			
	Wheat	Corn	Sunflower	Rapeseed
Tillage	Skimming (8–10 cm) Ploughing (20–22 cm) Deep loosening (40 cm) Spring harrowing	Skimming (8–10 cm) Ploughing (25–27 cm)	Skimming (8–12 cm) Ploughing (25–27 cm) Harrowing	Skimming (8–10 cm) Ploughing (22–24 cm) Cultivation (5–7 cm) Harrowing
Sowing	Date: 20 September–5 October Pre-sowing cultivation (6–8 cm) Seeding rate: (40.0–50.0) $\times 10^5$ seeds per hectare Rolling Harrowing	Date:1 May–10 May Pre-sowing cultivation (6–8 cm) Seeding rate: (0.8–1.0) $\times 10^5$ seeds per hectare Rolling	Date: 10 April–1 May Pre-sowing cultivation (5–7 cm) Seeding rate: (0.4–0.6) $\times 10^5$ seeds per hectare Rolling	Date: August Pre-sowing cultivation (3–4 cm) Seeding rate: 6.0 $\times 10^5$ seeds per hectare
Irrigation	1200–1500 m^3/ha	3900–4500 m^3/ha	1240–1500 m^3/ha	1030–1500 m^3/ha
Fertilization	$N_{40}P_{10}K_{10}$	$N_{60}P_{60}K_{60}$	$N_{50}P_{50}K_{50}$	$N_{95}P_{50}K_{30}$
Weed control	Chemicals: 2.4-D–1.4 kg/ha; Sumi-Alfa–0.25 L/ha	Inter-row cultivation Chemicals: Harnesы–2.5 L/ha	Inter-row cultivation Chemicals: Reglon–1L/ha	Inter-row cultivation Chemicals: Cineb–2.4 kg/ha; Sumicidin–0.3 L/ha
Harvesting	July	October	September	July

The experiments were conducted over five years on irrigated lands. They were designed at five farms located in the Kherson province for oilseed and grain crops (winter rapeseed, sunflower, winter wheat, and corn). We used the method of randomized split plots. There were forty plots. During a five-year field experiment, we explored the impact of a low-cost smart irrigation system on crop yield, water-use productivity, and economic benefits.

2.4. Component and Functions of a Smart Irrigation System

The main goal of any smart irrigation system is to decrease production costs and, therefore, to increase benefit. The saving of water, energy, fertilizer, and chemicals are expected from the system. The saving must not cut yield. In conventional irrigation systems, field technicians make decisions. A traditional strategy is normally based on soil moisture control. The methods used by farmers to calculate the irrigation rate are based on the calculation of soil moisture. It does not take into account many factors, including transpiration from the plants and terrain features. Therefore, the calculations are inaccurate, and their results exceed the required needs by 20–30%. Over-irrigation results in waterlogging, reduced air in the soil, the development of anaerobic bacteria, degradation, and significant economic costs. This irrigation scheduling strategy is implemented manually.

Our automatic system of control collects data, analyzes them, and makes the decision on irrigation. It uses information about soil conditions, weather, and climate data to schedule watering. The system monitors the quantity and timing of irrigating.

The Rain-1 module is a specially developed set of software and hardware for center pivot sprinkler machines (Fregat, Zimmatic, Bauer, etc.) based on GPS and GPRS modules for determining and transmitting operational data of irrigation systems. This module analyzes irrigation efficiency, vegetation, and soil moisture with daily satellite imagery using the following online services:

- vegetation index
- normalized difference vegetation index
- heterogeneity of plants
- humidity index
- heterogeneity of moisture

Its use provides some advantages. It allows the controlling of the operation of the irrigation system remotely. A satellite data analysis allows farmers to adjust irrigation decisions to maximize crop yield growth. This module allows switching to night watering to save money.

It is inexpensive. It may be customized for specific crops, soil, and weather conditions. The system receives information from a satellite and automatically determines crop evapotranspiration. Furthermore, it generates a program for the controller. A signal is transmitted to the actuators of an irrigation system. The automatic system of control (Figure 3) can be integrated into any irrigation machines.

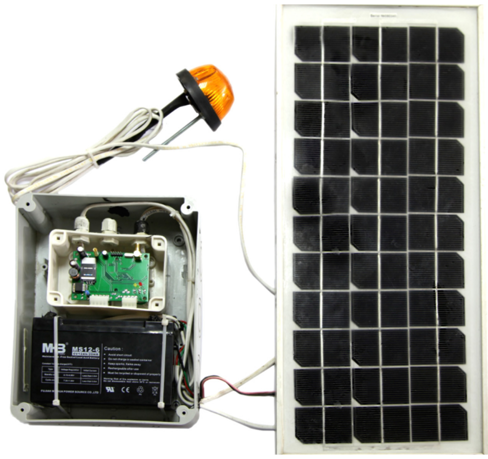


Figure 3. Automated irrigation quality control system *Rain-1*.

This system displays all data on the operation of the sprinklers. It shows a list of used sprinklers. The green circles are used for the working machines. The stopped machines are shown in orange. Moreover, there is information concerning the downtime and the irrigation rates. The colored chart shows the watering rates. The bright green color corresponds to the set norm of outflow, the darker color is above the norm, and the lighter is below (Figure 4). Based on this information (regarding soil moisture content), the module generates a program for an irrigation system. It determines the necessary amount of water supply for each sector of a plot. Figure 4 depicts current information about eight irrigated fields that are served by auto-mated irrigation quality control system *Rain-1*. The top left of the diagram displays the following information for field 6. The irrigation machine is not working (stopped). This machine has made five circles. And this is the twenty-fourth day of growing process. The top right of the diagram displays information about the operational status of the machine (on), its water meter (on) and field area (11 ha). The same information can be obtained for all fields.

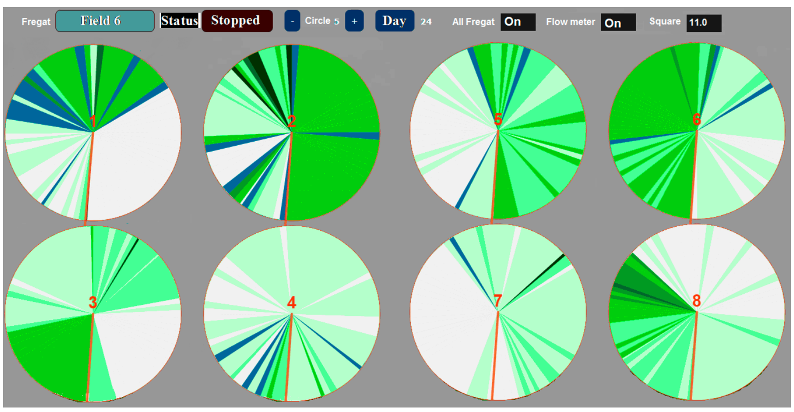


Figure 4. Operating diagram of an irrigation machine.

2.5. Water-Use Efficiency

The water consumed is equal to the sum of rainfall and irrigation. The water-use productivity is calculated as the ratio of the crop yield to the seasonal water consumed (rainfall and irrigation) [36,37].

$$WUP = CY \cdot WC^{-1},\ \mathrm{kg/m^3}, \tag{1}$$

where CY is the crop yield, kg/ha, and WC is the water consumed, m^3/ha.

The irrigated water-use productivity is

$$IWUP = CY \cdot IWC^{-1},\ \mathrm{kg/m^3}, \tag{2}$$

where IWC is the irrigated water consumed, m^3/ha.

We compared the water-use productivity and the financial costs for two irrigation strategies: fixed interval irrigation (a base variant); an optimal schedule and distribution. Irrigation scheduling determines when and how much to irrigate. Optimal scheduling maximizes profitability. The scheduling maintains optimal soil moisture by monitoring soil moisture, weather conditions, crop conditions, and predicting soil moisture to achieve it.

Crop yields were measured at harvest time. Yields were determined by the method of mechanized harvesting. We used the following formula:

$$CY = Mn \cdot PA^{-1},\ \mathrm{kg/ha}, \tag{3}$$

where Mn is the mass of crop from a field, kg, and AF is the plot area, ha.

The irrigation rate is based on the water balance method [38].

2.6. Economic Indicators

We determined two economic indicators: the increase in the income of the harvested crop and the payback period for additional capital investments. To determine the economic efficiency, we considered both the change in yield and the cost of water for irrigation. A payback period is used as an economic criterion. It is calculated as a ratio of investment costs (to retrofit a conventional irrigation system into a smart one) to return (economic benefits from the application of the smart irrigation system).

2.7. Statistical Analysis

The obtained experimental data were processed, tabulated, and statistically analyzed. The actual yield percent deviation from different irrigation systems was calculated by the following formula:

$$dCY = 100 \cdot \frac{CYs - CYc}{CYc},\ \%, \tag{4}$$

where CYc is the crop yield for a conventional irrigation system, kg/ha, and CYs is the crop yield for a smart irrigation system, kg/ha.

3. Results and Discussion

3.1. Water-Use Productivity

Table 3 illustrates the effect of the smart irrigation system on crop water-use productivity. The table shows the average data from the five years of our research. During the five-year experiments, the amounts of applied irrigation water were as follows: winter wheat—from 1220 to 1500 m^3/ha; corn—from 3900 to 4500 m^3/ha; sunflower—from 1240 to 1500 m^3/ha; rapeseed—from 1030 to 1500 m^3/ha. The yields of crops were in the following ranges: winter wheat—from 5490 to 6980 kg/ha; corn—from 11,040 to 14,240 kg/ha; sunflower—from 2380 to 3290 kg/ha; rapeseed—from 2800 to 3390 kg/ha.

Table 3. Crop Water-Use Productivity.

Locatiom	Irrigation System	Yield, kg/ha	Rainfall, mm	Irrigation, mm	GIW, m^3	WUP, kg/m^3	IWUP, kg/m^3
				wheat			
Farm 1	ICS	6980	444	148	5920	1.18	4.72
	SIS	6870	444	122	5660	1.21	5.63
Farm 2	ICS	6370	435	141	5760	1.11	4.52
	SIS	6410	435	126	5610	1.14	5.09
Farm 3	ICS	5970	398	147	5450	1.10	4.06
	SIS	6030	398	135	5330	1.13	4.47
Farm 4	ICS	5490	365	150	5150	1.07	3.66
	SIS	5640	365	141	5060	1.11	4.00
Farm 5	ICS	5600	401	142	5430	1.03	3.94
	SIS	5999	401	134	5350	1.12	4.48
				corn			
Farm 1	ICS	13000	444	410	8540	1.52	3.17
	SIS	13900	444	401	8450	1.64	3.47
Farm 2	ICS	14240	435	435	8700	1.64	3.27
	SIS	13970	435	395	8300	1.68	3.54
Farm 3	ICS	12280	398	430	8280	1.48	2.86
	SIS	12950	398	401	7990	1.62	3.23
Farm 4	ICS	11040	365	450	8150	1.35	2.45
	SIS	12180	365	432	7970	1.53	2.82
Farm 5	ICS	12650	401	426	8270	1.53	2.97
	SIS	13160	401	390	7910	1.66	3.37
				sunflower			
Farm 1	ICS	3020	435	145	5800	0.52	2.08
	SIS	3195	435	124	5590	0.57	2.58
Farm 2	ICS	3000	398	145	5430	0.55	2.07
	SIS	3190	398	138	5360	0.60	2.31
Farm 3	ICS	2380	365	150	5150	0.46	1.59
	SIS	2510	365	134	4990	0.50	1.87
Farm 4	ICS	2710	401	144	5450	0.50	1.88
	SIS	3090	401	148	5490	0.56	2.09
Farm 5	ICS	3020	435	145	5800	0.52	2.08
	SIS	3195	435	124	5590	0.57	2.58
				rapeseed			
Farm 1	ICS	3380	444	120	5640	0.60	2.82
	SIS	3390	444	103	5470	0.62	3.29
Farm 2	ICS	3180	435	137	5720	0.56	2.32
	SIS	3270	435	122	5570	0.59	2.68
Farm 3	ICS	2990	398	150	5480	0.55	1.99
	SIS	3170	398	139	5370	0.59	2.28
Farm 4	ICS	2800	365	150	5150	0.54	1.87
	SIS	2870	365	144	5090	0.56	1.99
Farm 5	ICS	2900	401	142	5430	0.53	2.04
	SIS	3085	401	131	5320	0.58	2.35

ICS—conventional irrigation system; SIS—smart irrigation system; GIW—gross irrigation water consumption; WUP—water-use productivity; IWUP—irrigated water-use productivity.

The use of smart irrigation technology allows us to reduce water consumption compared to a conventional irrigation system. Figure 5 shows the average results for the five-year field experiments for all five farms. The best result of 17.72% is observed for sunflower production. The lowest outcome of 11.57% is revealed for corn (Figure 5).

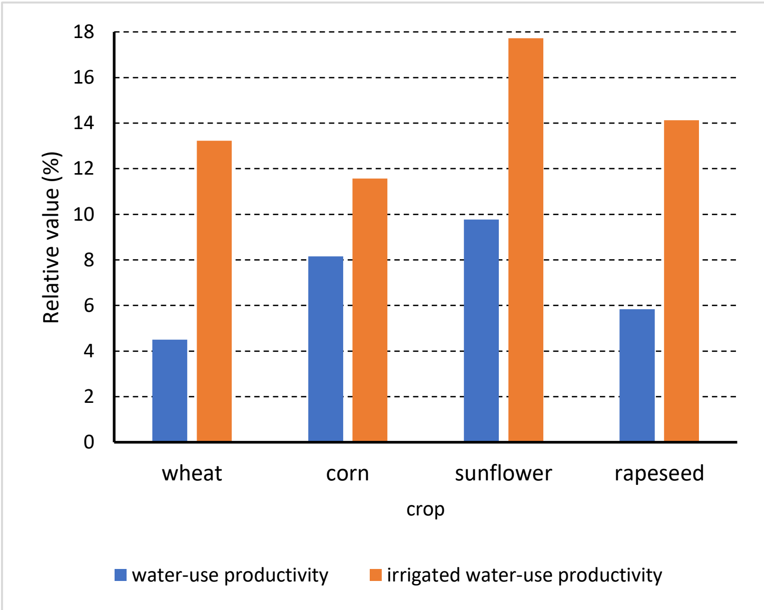


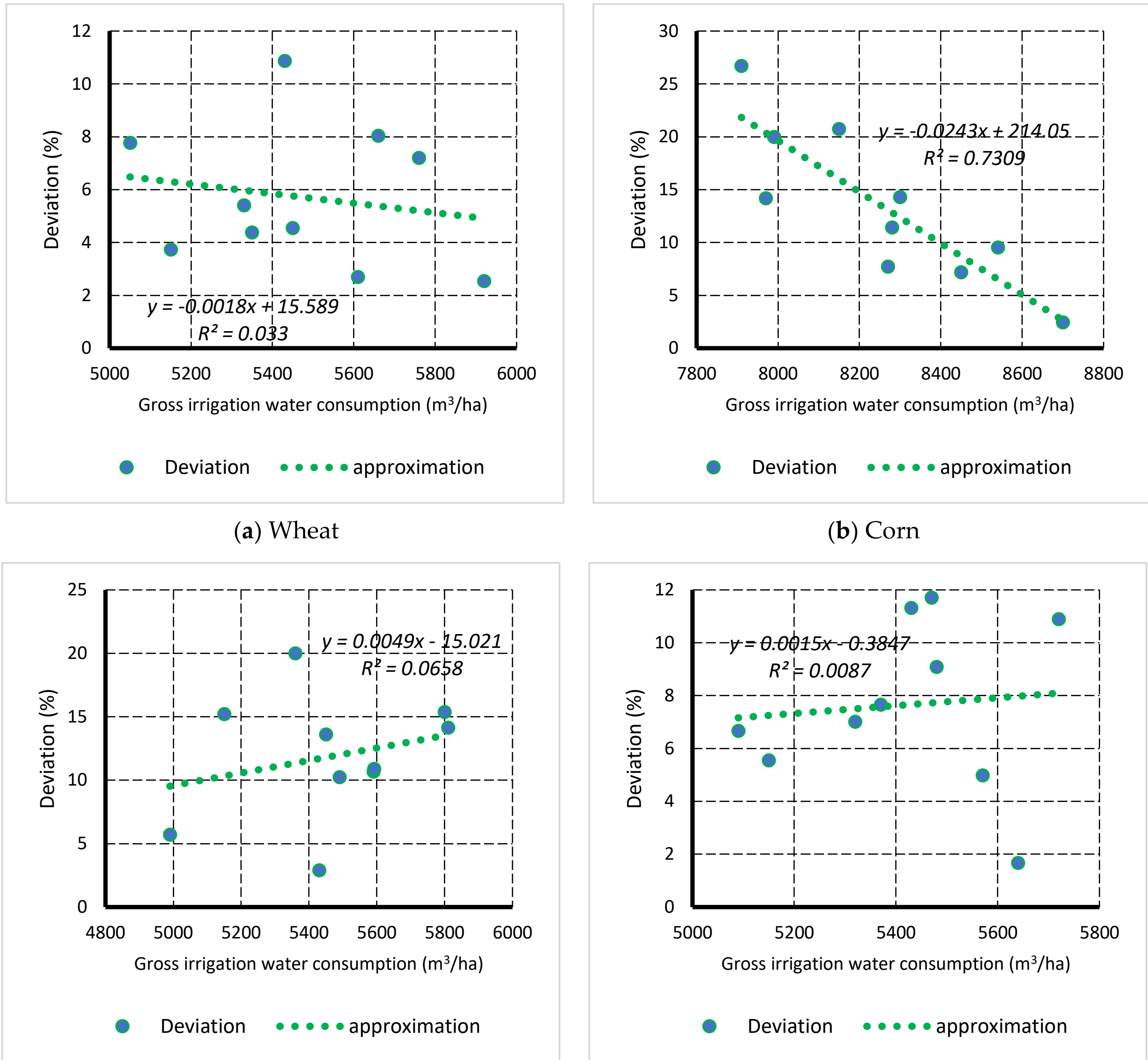
Figure 5. A relative increase in water-use productivity of smart irrigation systems compared to conventional ones.

Our obtained results are consistent with the results of other studies. The water-use productivity of wheat ranges from 0.4 (Uttar Pradesh West, India) to 2.08 kg/m^3 (Wangtong, China). Corn has better water-use productivity. It varies from 0.55 (Tanzania) to 3.33 kg/m^3 (USA) [39]. Vozhehova et al. [40] studied corn production on irrigated land in the south of Ukraine. They found that the lowest water-use productivity (0.5149 kg/m^3) was provided by disk cultivation (depth of 12 to 14 cm) and zero fertilizer. The highest WUP of 2.525 kg/m^3 was determined with shallow disk cultivation of 8 to 12 cm and fertilizer application rate of $N_{180}P_{60}$. Djaman et al. [41] found that the WUP of canola is in the range of 0.31 to 0.5 3.33 kg/m^3. This depends on a cultivar, a tillage practice, nutrition, and irrigation regime.

Sunflower seed production on irrigated land gives high benefits. Saeed et al. [42] found it had a maximum water-use productivity of 6.14 kg/m^3. Petrova et al. [43] give similar results. Albaji et al. [44] studied the water-use efficiency of sunflower seeds in the south-west of Iran. They reported that irrigated water-use productivity ranges from 1.16 to 3.024 kg/m^3. Our experiments showed that irrigated water-use productivity varied from 1.59 to 2.58 kg/m^3.

3.2. Relationship between Deviation of Yield and Gross Water Consumption

Field experiments revealed a significant deviation of yields (Figure 6). Corn and sunflower had the highest values (up to 20–27%). Wheat and rapeseed were characterized by a much smaller deviation of their yields (up to 11–12%). The main reason for the increase in yield is as follows: an advanced technology prolongs optimal soil water content during a growing spell. Moreover, it decreases water erosion, runoff, and nutrient status. There was a moderate (R^2 = 0.7309) linear relationship between the deviation of corn yield and gross water consumption. Whereas there was a poor (R^2 = 0.033 to 0.0087) relationship for wheat, sunflower, and rapeseed. This is evidence that other factors have an influence on the above relationships. These factors should be subject to further study.



(**a**) Wheat (**b**) Corn

(**c**) Sunflower (**d**) Rapeseed

Figure 6. The relationship between the deviation of yield and gross water consumption.

The slope of the lines demonstrates that for wheat and corn, an increase in the water use rate leads to a decrease in the efficiency of the proposed irrigation system. Whereas for oilseeds (sunflower and rapeseed), the character of lines is the opposite. An increase in the irrigation rate improves the efficiency of a low-cost irrigation system. This leads to a greater increase in yield.

Our results coincide with other studies. Araya et al. [45] reported that proper water management practices could improve wheat yield by 7–20%. Supplemental irrigation must be carried out with acceptable accuracy to reach a maximum effect [46].

Minimum, maximum, and average increases in water-use productivity are presented in Table 4. The values given in the table show that corn and sunflower have the highest rise in WUP. Wheat has lower values. Sunflower has a higher minimum increase in WUP. Therefore, a low-cost irrigation system for sunflowers gives the best results compared to other examined crops.

Table 4. Minimum, maximum, and average increases in water-use productivity (%).

Crop	Minimum	Maximum	Average
Wheat	2.54	8.74	4.09
Corn	2.44	13.33	8.32
Sunflower	8.69	12.00	9.80
Rapeseed	3.33	9.43	5.82

3.3. Economic Efficiency

Economic efficiency is determined based on the following data: investment costs in a smart irrigation system; operational costs of a smart irrigation system; yields; crop prices; water-saving; price of water; plot area. We propose the determination of a specific return (the difference between the values of the crop grown using different irrigation systems). Its value is suggested to be calculated by the following formula:

$$SR = (CP \cdot CYs - WP \cdot WCs) - (CP \cdot CYc - WP \cdot WCc), \text{USD/ha}, \quad (5)$$

where CYc is the yield under a conventional irrigation system, kg/m^3; CYs is the yield under smart irrigation system, kg/m^3; CP is the crop price, USD/kg; WP is the price of water, USD/m^3; WCs is the irrigated water consumed by the low-cost smart irrigation system, m^3/ha; and WCc is the irrigated water consumed by the conventional irrigation system, m^3/ha.

The irrigated water consumed can be calculated using the formulas:

$$WCs = \frac{CYs}{IWUPs}, \text{m}^3/\text{ha} \quad (6)$$

and

$$WCc = \frac{CYc}{IWUPc}, \ \text{m}^3/\text{ha}. \quad (7)$$

After transformation, we obtain the final equation for determining the specific return:

$$SR = CP \cdot (CYs - CYc) + WP \cdot \left(\frac{CYc}{IWUPc} - \frac{CYs}{IWUPs} \right), \ \text{USD/ha}. \quad (8)$$

We suggest calculating a payback period using the following formula:

$$PBP = IC \cdot (SR \cdot PA + OC)^{-1}, \ \text{year}, \quad (9)$$

where IC is the investment costs of a smart irrigation system, USD; OP is the operating costs, USD/year; and PA is the plot area, ha.

In our calculations, we assumed the following initial data: investment costs—USD2260; operating costs (operation, management, maintenance, repair, replacement)—USD1300/year [47]; the price of water—from USD0.050/m^3 to USD0.083/m^3; the plot area—41 and 50 ha (actual values). Actual crop prices were as follows: USD/t: wheat—300.4; corn—278.3; sunflower seeds—649.4; rapeseed—728.9 [48]. The smart irrigation system gives the best result for corn production. This system allows farmers to increase income in the range from USD40/ha to USD185/ha (Figure 7).

We found payback periods for additional investment costs to convert a conventional irrigation system into a low-cost smart irrigation system. Payback periods are calculated for different crops and plot areas. The application of smart irrigation systems for wheat production has the worst result. Corn production covers investment costs faster than other crops (Figure 8). The main reason for this is that corn production has the highest specific return (Figure 7). The influence of a plot area on the payback period depends on the specific return. The increase in the area leads to a decrease in the payback period of investment costs. Results for wheat confirm the above idea.

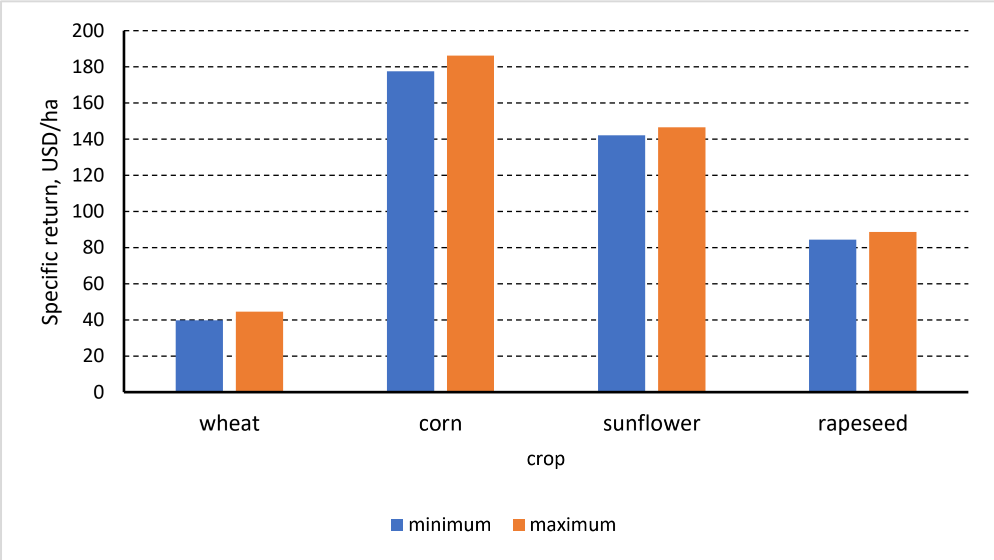


Figure 7. An increase in crop production income from the use of low-cost irrigation systems.

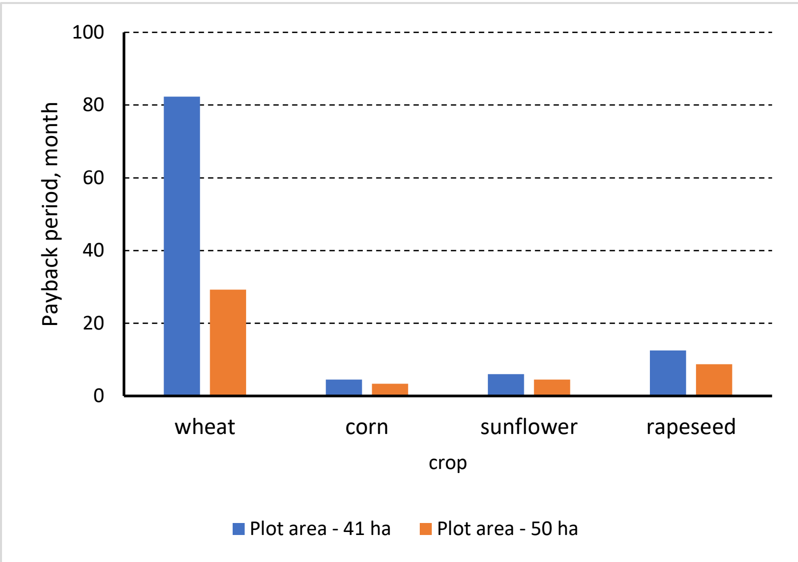


Figure 8. Payback periods for the retrofitting of the conventional irrigation system.

4. Conclusions

Ukraine has highly developed agriculture. Modern irrigation technologies are needed for sustainable agricultural production. They are rather expensive. However, existing irrigation systems can be improved by simple and relatively cheap solutions.

Five-year field experiments have proven that the Rain-1 module improves the irrigation water-use productivity. The smart irrigation system reduces irrigation water consumption. Its irrigated water-use productivity is less (by 11–17%) compared to conventional irrigation systems. This is possible due to optimized water supply and timing. The lowest IWUP is recorded for wheat, while the highest value is for sunflowers.

The specific return is proposed as an indicator for the economic assessment of irrigation systems. The economic efficiency of smart irrigation technologies depends on the specific return of any crop. In our study, the application of smart irrigation gives better results for sunflower, rapeseed, and corn. For the Rain-1 module, a payback period ranges from 3.8 to 82 months. If there is a cultivation of corn, sunflower, and rapeseed, the payback period can be less than one year.

An economic benefit is achieved with irrigation water saving and proper water distribution. Our study has demonstrated that the existing conventional irrigation systems can be retrofitted with the Rain-1 module to improve water management. Therefore, the application of this module may be recommended.

Agriculture is an energy-intensive industry. It emits around 25% of the total greenhouse gases [49,50]. Energy and environmental analyses of low-cost smart irrigation systems are the subjects of further study. They are planned to be implemented using mathematical models tested in previous publications [51–53].

Pressurized irrigation systems are energy-intensive. An increase in energy costs results in higher production costs and, therefore, a reduction of profitability [54]. The share of energy can reach 40–65% of total operational costs [9,55]. For this reason, an energy analysis will be the subject of further study.

Author Contributions: Conceptualization, V.H.; methodology, V.H. and V.N.; software, O.B. and S.L.; validation, V.H. and Y.M.; formal analysis, V.H. and V.N.; investigation, O.B. and V.N.; resources, O.B.; data curation, Y.M. and S.L.; writing—original draft preparation, V.H. and V.N.; writing—review and editing, O.B. and Y.M.; visualization, Y.M. and S.L.; supervision, V.H. and Y.M.; project administration, O.B.; funding acquisition, O.B. All authors have read and agreed to the published version of the manuscript.

Funding: This study was carried out as part of the project "Belt and Road Initiative Institute for Chinese–European studies" and was funded by the Guangdong University of Petrochemical Technology, Maoming, China.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing not applicable.

Acknowledgments: Thanks to Guangdong University of Petrochemical Technology for supporting and donating this research.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Alexandratos, N.; Bruinsma, J. *World Agriculture Towards 2030/2050: The 2012 Revision*; ESA Work. Pap. No.12–03; FAO: Rome, Italy, 2012; p. 153. Available online: http://www.fao.org/3/ap106e/ap106e.pdf (accessed on 2 October 2021).
2. Pereira, L.S. Water, Agriculture and Food: Challenges and Issues. *Water Resour. Manag.* **2017**, *31*, 2985–2999. [CrossRef]
3. Hassan, W.; Kamran, F. A hybrid PV/utility powered irrigation water pumping system for rural agricultural areas. *Cogent Eng.* **2018**, *5*, 1466383. [CrossRef]
4. Kassas, M. Aridity, drought and desertification. In *Arab Environment Future Challenges*; Arab Forum for Environment and Development: Beirut, Lebanon, 2008; pp. 95–110. Available online: https://research.fit.edu/media/site-specific/researchfitedu/coast-climate-adaptation-library/middle-east/regional---middle-east/Tolba--Saab.-2008.-Middle-East-Arab-Environments-Future-Challenges.pdf (accessed on 22 September 2021).
5. Arable Land By Country. 2021. Available online: https://worldpopulationreview.com/country-rankings/arable-land-by-country (accessed on 22 September 2021).
6. Agricultural Irrigated Land (% of Total Agricultural Land)-Country Ranking. Available online: https://www.indexmundi.com/facts/indicators/AG.LND.IRIG.AG.ZS/rankings (accessed on 22 September 2021).
7. Lykhovyd, P. Irrigation Needs in Ukraine According to Current Aridity Level. *J. Ecol. Eng.* **2021**, *22*, 11–18. [CrossRef]
8. *Review of World Water Resources by Country*; Food and Agriculture Organization of The United Nations: Rome, Italy, 2003. Available online: https://www.fao.org/3/y4473e/y4473e00.htm (accessed on 22 November 2021).
9. Ladychuk, D.; Shaporynska, N.; Lavrenko, S.; Lavrenko, N. The methods for determining agrolandscape typicality for projects of water supply construction. *AgroLife Sci. J.* **2021**, *10*, 121–129.
10. García, I.F.; Montesinos, P.; Poyato, E.C.; Díaz, J.R. Optimal design of pressurized irrigation networks to minimize the operational cost under different management scenarios. *Water Resour. Manag.* **2017**, *31*, 1995–2010. [CrossRef]
11. European Commission. *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions*; The European Green Deal. COM/2019/640 Final; European Commission: Brussels, Belgium, 2019. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640 (accessed on 20 October 2021).

12. Chukurna, O.; Nitsenko, V.; Kralia, V.; Sahachko, Y.; Morkunas, M.; Volkov, A. Modelling and Managing the Effect of Transferring the Dynamics of Exchange Rates on Prices of Machine-Building Enterprises in Ukraine. *Pol. J. Manag. Stud.* **2019**, *19*, 117–129. [CrossRef]
13. Gnatyuk, V.A. Mechanism of laser damage of transparent semiconductors. *Phys. B Condens. Matter* **2001**, *308–310*, 935–938. [CrossRef]
14. García, L.; Parra, L.; Jimenez, J.M.; Lloret, J.; Pascal Lorenz, P. IoT-Based Smart Irrigation Systems: An Overview on the Recent Trends on Sensors and IoT Systems for Irrigation in Precision Agriculture. *Sensors* **2020**, *20*, 1042. [CrossRef]
15. Havrysh, V.; Hruban, V.; Sadovoy, O.; Batsurovska, I.; Fedorchuk, V.; Yablunovskaya, K. Energy Saving Technologies for Automatical Move Irrigation Equipment. In Proceedings of the 2020 IEEE Problems of Automated Electrodrive. Theory and Practice (PAEP), Kremenchuk, Ukraine, 21–25 September 2020; pp. 1–4. [CrossRef]
16. Lavrenko, S.O.; Lavrenko, N.M.; Maksymov, D.O.; Maksymov, M.V.; Didenko, N.O.; Islam, K.R. Variable tillage depth and chemical fertilization impact on irrigated common beans and soil physical properties. *Soil Tillage Res.* **2021**, *212*, 105024. [CrossRef]
17. Zamula, I.; Tanasiieva, M.; Travin, V.; Nitsenko, V.; Balezentis, T.; Streimikiene, D. Assessment of the Profitability of Environmental Activities in Forestry. *Sustainability* **2020**, *12*, 2998. [CrossRef]
18. Canaj, K.; Parente, A.; D'Imperio, M.; Boari, F.; Buono, V.; Toriello, M.; Mehmeti, A.; Montesano, F.F. Can Precise Irrigation Support the Sustainability of Protected Cultivation? A Life-Cycle Assessment and Life-Cycle Cost Analysis. *Water* **2022**, *14*, 6. [CrossRef]
19. Incrocci, L.; Thompson, R.B.; Fernandez-Fernandez, M.D.; De Pascale, S.; Pardossi, A.; Stanghellini, C.; Rouphael, Y.; Gallardo, M. Irrigation management of European greenhouse vegetable crops. *Agric. Water Manag.* **2020**, *242*, 106393. [CrossRef]
20. Domínguez-Niño, J.M.; Oliver-Manera, J.; Girona, J.; Casadesús, J. Differential irrigation scheduling by an automated algorithm of water balance tuned by capacitance-type soil moisture sensors. *Agric. Water Manag.* **2020**, *228*, 105880. [CrossRef]
21. Cáceres, G.; Millán, P.; Pereira, M.; Lozano, D. Smart Farm Irrigation: Model Predictive Control for Economic Optimal Irrigation in Agriculture. *Agronomy* **2021**, *11*, 1810. [CrossRef]
22. Ostapenko, R.; Herasymenko, Y.; Nitsenko, V.; Koliadenko, S.; Balezentis, T.; Streimikiene, D. Analysis of Production and Sales of Organic Products in Ukrainian Agricultural Enterprises. *Sustainability* **2020**, *12*, 3416. [CrossRef]
23. Bazaluk, O.; Yatsenko, O.; Zakharchuk, O.; Ovcharenko, A.; Khrystenko, O.; Nitsenko, V. Dynamic Development of the Global Organic Food Market and Opportunities for Ukraine. *Sustainability* **2020**, *12*, 6963. [CrossRef]
24. Shvets, V.Y.; Rozdobudko, E.V.; Solomina, G.V. Aggregated methodology of multicriterion economic and ecological examination of the ecologically oriented investment projects. *Nauk. Visnyk Natsionalnoho Hirnychoho Universytetu* **2013**, *3*, 139–144.
25. Koval, V.; Mikhno, I.; Udovychenko, I.; Gordiichuk, Y.; Kalina, I. Sustainable natural resource management to ensure strategic environmental development. *TEM J.* **2021**, *10*, 1022–1030. [CrossRef]
26. Malik, W.; Dechmi, F. DSSAT modelling for best irrigation management practices assessment under mediterranean conditions. *Agric. Water Manag.* **2019**, *216*, 27–43. [CrossRef]
27. Abrishambaf, O.; Faria, P.; Gomes, L.; Vale, Z. Agricultural irrigation scheduling for a crop management system considering water and energy use optimization. *Energy Rep.* **2020**, *6*, 133–139. [CrossRef]
28. Dong, X.; Vuran, M.C.; Irmak, S. Autonomous precision agriculture through integration of wireless underground sensor networks with center pivot irrigation systems. *Ad Hoc Netw.* **2013**, *11*, 1975–1987. [CrossRef]
29. Boobalan, J.; Jacintha, V.; Nagarajan, J.; Thangayogesh, K.; Tamilarasu, S. An IOT based agriculture monitoring system. In Proceedings of the 2018 International Conference on Communication and Signal Processing, Tamilnadu, India, 3–5 April 2018; IEEE: Piscataway, NJ, USA, 2018; pp. 0594–0598. [CrossRef]
30. Pernapati, K. IoT based low cost smart irrigation system. In Proceedings of the 2018 Second International Conference on Inventive Communication and Computational Technologies, Coimbatore, India, 20–21 April 2018; IEEE: Piscataway, NJ, USA, 2018; pp. 1312–1315. [CrossRef]
31. Brajovic, M.; Vujovic, S.; Dukanovic, S. An overview of smart irrigation software. In Proceedings of the 2015 4th Mediterranean Conference on Embedded Computing, Budva, Montenegro, 14–18 June 2015; IEEE: Piscataway, NJ, USA, 2015; pp. 353–356. [CrossRef]
32. Munir, M.S.; Bajwa, I.S.; Ashraf, A.; Anwar, W.; Rashid, R. Intelligent and Smart Irrigation System Using Edge Computing and IoT. *Complexity* **2021**, *2021*, 6691571. [CrossRef]
33. Monthly and Annual Precipitation in Kherson. 2021. Available online: http://www.pogodaiklimat.ru/history/33902_2.htm (accessed on 14 October 2021).
34. Ayers, R.S.; Westcot, D.W. Water Quality for Agriculture. In *FAO Irrigation and Drainage*; Paper 29 Rev. 1; FAO: Rome, Italy, 1985. Available online: http://www.fao.org/3/t0234e/t0234e.pdf (accessed on 22 October 2021).
35. Likhovid, P.V. Analysis of the Ingulets irrigation water quality by agronomical criteria. *Success Mod. Sci. Educ.* **2015**, *5*, 10–12. [CrossRef]
36. Ali, M.H.; Talukder, M.S.U. Increasing water productivity in crop production–A synthesis. *Agric. Water Manag.* **2008**, *95*, 1201–1213. [CrossRef]
37. Howell, T.A. Enhancing water use efficiency in irrigated agriculture. *Agron. J.* **2001**, *93*, 281–287. [CrossRef]
38. FAO. *Soil Testing Methods–Global Soil Doctor Programme–A Farmer-to-farmer Training Programme*; FAO: Rome, Italy, 2020. Available online: http://www.fao.org/3/ca2796en/CA2796EN.pdf (accessed on 7 October 2021).

39. Foley, D.J.; Thenkabail, P.S.; Aneece, I.P.; Teluguntla, P.G.; Oliphant, A.J. A meta-analysis of global crop water productivity of three leading world crops (wheat, corn, and rice) in the irrigated areas over three decades. *Int. J. Digit. Earth* **2020**, *13*, 939–975. [CrossRef]
40. Vozhehova, R.A.; Maliarchuk, M.P.; Biliaieva, I.M.; Markovska, O.Y.; Maliarchuk, A.S.; Tomnytskyi, A.V.; Lykhovyd, P.V.; Kozyrev, V.V. The effect of tillage system and fertilization on corn yield and water use efficiency in irrigated conditions of the South of Ukraine. *Biosyst. Divers.* **2019**, *27*, 125–130. [CrossRef]
41. Djaman, K.; O'Neill, M.; Owen, C.; Smeal, D.; West, M.; Begay, D.; Angadi, S.V.; Koudahe, K.; Allen, S.; Lombard, K. Seed Yield andWater Productivity of Irrigated Winter Canola (*Brassica napus* L.) under Semiarid Climate and High Elevation. *Agronomy* **2018**, *8*, 90. [CrossRef]
42. Saeed, A.A.Q.; Abdel-Nasser, G.; Gomaa, M.A. Growth, Productivity and Water Use of Sunflower Crop Under Drip Irrigation System. *J. Adv. Agric. Res.* **2015**, *20*, 420–437.
43. Petrova, R.; Matev, A.; Kirchev, H.; Sevov, A. Productivity of sunflower grown in a periodic water deficit conditions. *Agric. Sci. Technol.* **2013**, *5*, 39–45.
44. Albaji, M.; Nasab, S.B.; Behzad, M.; Naseri, A.A.; Shahnazari, A.; Meskarbashee, M.; Judy, F.; Jovzi, M.; Shokoohfar, A.R. Water productivity and water use efficiency of sunflower under conventional and limited irrigation. *J. Food Agric. Environ.* **2011**, *9*, 202–209. [CrossRef]
45. Araya, A.; Prasad, P.V.V.; Ciampitti, I.A.; Jha, P.K. Using crop simulation model to evaluate influence of water management practices and multiple cropping systems on crop yields: A case study for Ethiopian highlands. *Field Crops Res.* **2021**, *260*, 108004. [CrossRef]
46. Jha, P.K.; Kumar, S.N.; Ines, A.V.M. Responses of soybean to water stress and supplemental irrigation in upper Indo-Gangetic plain: Field experiment and modeling approach. *Field Crops Res.* **2018**, *219*, 76–86. [CrossRef]
47. Dispatching the Work of Sprinklers. Available online: http://products.vidcompro.net/dispetcherizatsiya-rabotyi-dozhdevalnyih-mashin/ (accessed on 9 March 2022).
48. Agrotender. Available online: https://agrotender.com.ua/traders/region_ukraine/raps (accessed on 13 October 2021).
49. Marshall, M.; Thenkabail, P. Developing In Situ Non-destructive Estimates of Crop Biomass to Address Issues of Scale in Remote Sensing. *Remote Sens.* **2015**, *7*, 808–835. [CrossRef]
50. Vermeulen, S.J.; Challinor, A.J.; Thornton, P.K.; Campbell, B.M.; Eriyagama, N.; Vervoort, J.M.; Kinyangi, J.; Jarvis, A.; Läderach, P.; Ramirez-Villegas, J.; et al. Addressing Uncertainty in Adaptation Planning for Agriculture. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 8357–8362. [CrossRef]
51. Kotenko, S.; Nitsenko, V.; Hanzhurenko, I.; Havrysh, V. The Mathematical Modeling Stages of Combining the Carriage of Goods for Indefinite, Fuzzy and Stochastic Parameters. *Int. J. Integr. Eng.* **2020**, *12*, 173–180. [CrossRef]
52. Havrysh, V.; Kalinichenko, A.; Mentel, G.; Mentel, U.; Vasbieva, D.G. Husk Energy Supply Systems for Sunflower Oil Mills. *Energies* **2020**, *13*, 361. [CrossRef]
53. Bazaluk, O.; Havrysh, V.; Fedorchuk, M.; Nitsenko, V. Energy Assessment of Sorghum Cultivation in Southern Ukraine. *Agriculture* **2021**, *11*, 695. [CrossRef]
54. Perea, R.G.; Poyato, E.C.; Díaz, J.R. Forecasting of applied irrigation depths at farm level for energy tariff periods using Coactive neuro-genetic fuzzy system. *Agric. Water Manag.* **2021**, *256*, 107068. [CrossRef]
55. Rodríguez Díaz, J.; Camacho Poyato, E.; Blanco Pérez, M. Evaluation of water and energy use in pressurized irrigation networks in Southern Spain. *J. Irrig. Drain. Eng.* **2011**, *137*, 644–650. [CrossRef]