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Evaluation of Sustainability of Irrigated Crops in Arid Regions, China

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Abstract: Ensuring national food security amidst ongoing economic development whilst both protecting the environment and reducing the dependence on fossil fuels are significant challenges for Chinese sustainable development. The main objectives of this study were to reveal irrigated crop (wheat, maize, and sunflower) performance in terms of energy, economic, and environmental aspects in China's largest designed irrigation area, Hetao irrigation district (HID), and to evaluate agricultural suitability based on plant structure. An integrated indicator and comprehensively assessment method were used to evaluate the above objectives based on the results from in-person surveys. The results show that maize exhibits the best overall performance compared to two other major crops (wheat and sunflower), which supports the government policy of adjust and optimize the planting structure program (AOPST), an effective way to achieve the multiple-objectives for sustainable agricultural development. However, reducing fertilizer remains a more critical factor than AOPST. These study results provide useful guidance for policy-makers and relevant stake-holders both in a regional context for the HID and at the global agricultural governance and management level.

Keywords: net profit; energy use efficiency; environmental degradation; comprehensive assessment; agricultural sustainability

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1. Introduction

China has experienced the world's fastest economic development since the Open and Reform policy of 1978. However, the rapid rate of economic increase has come at the expense of environmental damage. China's CO_2 emissions tripled from 2000 to 2018, and China is the world's biggest CO_2 emitter [1]. China is also the world's largest energy consumer, with low-energy-efficient coal and (liquid) petroleum being the main source for Chinese energy resources [2]. Agriculture is one of the most important global greenhouse gas (GHG) emitters [3] and energy consumers [4]. However, Chinese agriculture has contributed considerably to the elimination of world hunger with only 7% of the world's arable land feeding 20% of the global population [5]. Chinese agricultural production depends heavily on fossil fuel energy, exogenous fertilizer, and pesticides, which have accelerated China's import dependency on other countries, especially from nations that are less stable politically [6]. As a consequence, this has had a negative impact on China's national stability and sustainability, which then threatens global food security [7]. China is the world's largest chemical fertilizer consumer, with nitrogen consumption accounting for 40% of global consumption [8]. The high N consumption intensive agriculture areas of China result in more than 10 million tons of reactive nitrogen loss (RNL) and a huge amount of GHG emissions annually, leading to environmental degradation and accelerating climate change [9,10]. Moreover, China's fast economic growth rate reduced the overall available amount of arable land, which negatively impacted domestic food supply. The economy

also drives farmers to grow high economic income crops and change agriculture planting structures, which might threaten national food security and social stability [11].

Recently, the concept of agricultural sustainable development (also referred to as agriculture green development) has been addressed [12–14] based on the integration of Chinese agricultural challenges and the United Nations' sustainable development goals (SDGs) [12,15]. The aim is to convert Chinese agriculture from a tremendous resource and energy consumption and high environmental costs system to a sustainable and green development system with multiple goals, including improving resource use efficiency, increasing economic benefits for farmers, reducing environmental risk, relieving energy consumption pressure, etc. [13]. Comprehensive assessment of agricultural sustainability is becoming an imperative method and a hot topic for evaluating the overall performance of systems with multiple goals. A large number of studies have assessed agricultural systems based on comprehensive assessments. Normally, economic, social, energetic, or environmental effects were commonly used to evaluate the crop performance or agricultural system sustainability. Oudshoorn et al. [16] estimated the economic and environmental consequences of three organic dairy farming systems in Denmark. Nakashima and Ishikawa [17] compared the performances of Japanese's current and alternative small-scale farmer sugarcane cropping systems in terms of energy use and GHG emissions. Unakıtan and Aydın [18] determined the energy use and economics of wheat and sunflower production in Turkey. Pashaei Kamali et al. [19] evaluated the sustainability performances (from the environmental, economic, and social aspects) of different soybean farming systems in Brazil. Li et al. [10], from agronomic, environmental, and economic perspectives, evaluated two typical intensive cereal crops in China.

In order to make every effort to ensure national food security, starting from 2006, the Chinese government began to use a series of economic instruments, i.e., food subsidies (FS), to support farmers to expand sown areas for food production to meet the nationally increasing food demand [20]. In 2016, the national adjustment and optimization of agricultural planning structure program from 2016 to 2020 (AOPST) was issued to adapt to the economic development and to advance the reform of the agricultural planting structure. The economic strategies were used at the national level to incentivize farmers to change their production patterns. For example, in Northeast China, expanding the soybean area by decreasing the maize area is encouraged. However, in the North region, with irrigation conditions such as the Hetao Irrigation District (HID), escalating the maize area is incentivized by the government [21,22]. The AOPST was immediately implemented in the HID after the national AOPST was issued. Wheat, maize, and sunflower are the major crops in this region. Although in different regions of the world, numerous studies have demonstrated the performance of wheat, maize, and sunflower from economic [23,24], energetic [24,25], and environmental points of view [26–28], comprehensive evaluation of the performance of those crops from multiple aspects is still lacking [29], and overall performance of those crops in HID have not been reported yet. The main purpose of AOPST in HID is to promote agricultural sustainability in the long term by changing production patterns (crop types). However, did the AOPST expand the maize area in this region? Whether it is an effective program to promote agricultural sustainability in HID from economic, environmental, and energy aspects is still unknown.

Therefore, the objectives of this are to (1) conduct a multi-dimensional and comprehensive comparison of three widely practiced crops (wheat, maize, and sunflower) in terms of economic, energetic, and environmental aspects in HID; (2) to identify the potential strategies of improvement of these crop production systems; (3) to evaluate, based on objective 2, the effectiveness of AOPST by a comprehensive assessment of agricultural sustainability; and (4) to provide suitable improvement strategies for local policy-makers and relevant stakeholders for future agricultural sustainable development.

2. Materials and Methods

2.1. Study Area

The HID is situated in the Yellow River Basin, Inner Mongolia Autonomous Region, North China (Figure 1). It is one of the major grain and oil-producing areas in China, which has made a large contribution to food security in North China and has played a pivotal role in agricultural production trade between Inner Mongolia Autonomous Region and its border countries (Russia and Mongolia). The HID has a long history of agricultural civilization dating from the Han dynasty. It is the largest gravity-fed irrigation district in Asia with an irrigated area of 5.74 × 103 km^2 [30], and in 2019 this area was listed on the world heritage list of irrigation projects. The climate in this region is arid continental monsoon, with hot and moist summers (annual average air temperature 23 °C, highest 35 °C) and dry and severely cold winters (annual average air temperature −10 °C, lowest −32 °C) [31]. The annual precipitation is around 150 mm, and the annual potential evaporation is 150 mm [32]. The Yellow River is the water source for irrigation in this area, where surface irrigation technology is mainly applied. Soils are classified as siltic irragric anthrosol in this region [33].

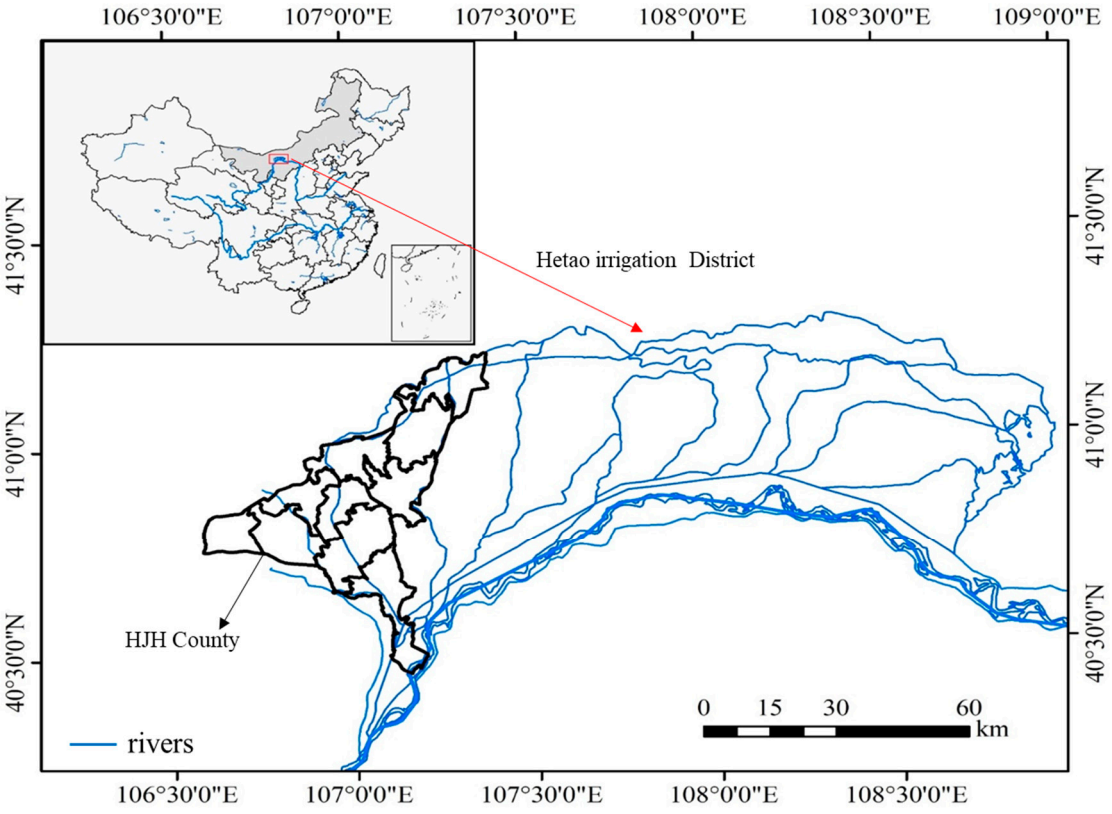

Figure 1. Study area in China.

2.2. Data Collection

Chinese agriculture has been smallholder based; hence, in this study, face-to-face interviews of the smallholder farmers were conducted for three major crops in Hangjinhou County (HJH), Inner Mongolia Autonomous Region, in 2019 as representatives of three typical crops on the HID region. The surveyed households were evenly distributed geographically over the research region following Cui et al. [34]. A total of nine towns of HJH were included, which accounted for 100% of the total acreage planted of the three crop production systems. In each town, two villages were selected; in each village, 3–5 households were randomly chosen as survey targets. Overall, valid data from 219 questionnaires (62 wheat households, 71 maize households, and 83 sunflower households)

were obtained for further analysis with a 10% sampling error margin and 95% confidence interval. The information of the three crops that were collected mainly included agronomic data (comprising crop sowing area, yield, fertilizer inputs, human labor, machinery, electricity, services, etc.) (Table 1), and economic data (containing itemized production costs and revenues).

Table 1. Resource inputs and production outputs of different crop systems in the arid region in 2019.

Item	Units	Wheat	Maize	Sunflower
Input				
Seed	kg/ha	419.1	30.4	4.97
Plastic film	kg/ha	0.0	36.8	34.32
Fertilizers				
Nitrogen (N)	kg/ha	352.7	388.75	248.2
Phosphorus (P_2O_5)	kg/ha	275.1	244.7	173.0
Potassium (K_2O)	kg/ha	44.5	22.09	23.2
Pesticides	kg/ha	4.19	4.91	5.82
Electricity	kwh/ha	0	0	15.5
Water	m^3/ha	3600.0	4360.0	3500.0
Human labor	h/ha	51.1	75.0	161.9
Farmyard manure	kg/ha	1741	5421	1668
Machinery	h/ha	31.71	50.51	44.11
Diesel fuel	kg/ha	158.8	214.7	127.1
Output				
Grain	kg/ha	4818.5	10,309.5	2914.6
Straw	kg/ha	6654.1	10,730.3	4134.3
Sunflower cake	kg/ha	0.0	0.0	950.2

2.3. Economic Assessment

The economic performances of three crops were calculated by the cost–benefit method [35]. Cost–benefit is a systematic economic approach to determine if an investment or decision is financially reasonable [35]. The cost includes labor inputs and all expenses of field operations, such as fertilizer, seed, biocides, plastic film, machinery cost (including both depreciation and maintenance cost), services, etc. (Table 2). The irrigation fee is charged by the planting area. Therefore, all the crops under the fixed unit (ha) have the same irrigation cost. Chinese smallholder farmers use the land for food production for free, and agricultural taxes have been eliminated since 2006. The land rent was not included in this study. The benefits consisted of income from harvested grain and by-products, and subsidies from FS and AOPST (Table 2). All the prices were expressed using USD ($), where 1 US$ was equal to 6.79 yuan (¥) in 2019 (www.xe.com/currencyconverter). Net profit (NP), benefit:cost ratio (BCR), and economic productivity (PR) are commonly used to reflect the economic performance of different crops [36]. Net profit (NP) is calculated as total production value ($/ha) minus total cost ($/ha), expressed as $/ha. The benefit:cost ratio (BCR) is the ratio between total production value and total cost. Economic productivity (PR) is the ratio between grain yield (kg/ha) and total cost ($/ha), expressed as kg/$.

2.4. Energy Assessment

Energy use performances of three crops were estimated by converting agronomic data, including inputs and outputs, into an energy unit (MJ) with the appropriate coefficients of energy equivalence (Table S1). The total energy inputs were divided into renewable energy (RE) and non-renewable energy (NRE). The RE consisted of seeds, labor, irrigation water, and farmyard manure, while NRE included machinery, diesel, fertilizer, biocides, and plastic film. Net energy (NE) is calculated as energy output minus energy input, expressed as MJ/ha. Energy use efficiency (EUE) is computed as the ratio between energy output and input. Specific energy (SE) is energy consumption per kg grain, expressed as MJ/kg.

Table 2. Economic analysis of different crops in the arid region in 2019.

Cropping Systems	Wheat		Maize		Sunflower	
Cost	$/ha	%	$/ha	%	$/ha	%
Seeds	292	18.3	98	5.7	166	10.2
Fertilizers	434	27.1	420	24.4	286	17.5
Plastic film	0	0.0	64	3.7	55	3.4
Pesticides	21	1.3	34	2.0	35	2.1
Irrigation	304	19.0	304	17.7	304	18.6
Diesel	176	11.0	239	13.9	141	8.6
Service	220	13.7	376	21.8	121	7.4
Electricity	0	0.0	0	0.0	1	0.1
Machinery	49	3.1	49	2.8	66	4.1
Self-labor	103	6.5	138	8.0	458	28.0
Total cost	1600		1721		1633	
Income	$/ha	%	$/ha	%	$/ha	%
Main-products	2377	87.4	2745	79.2	3110	89.3
By-products	176	6.5	308	8.9	207	5.9
Subsidies	166	6.1	411	11.9	166	4.8
Gross return	2718		3464		3482	
Calculation						
NP ($/ha)	1118		1743		1849	
BCR	1.70		2.01		2.13	
PR (kg/$)	3.01		5.99		1.78	

NP: net profit; BCR: benefit:cost ratio; PR: economic productivity.

2.5. Environmental Assessment

Following Chen et al. [37], reactive nitrogen losses (RNL) and GHG emissions were calculated to compare the environmental performance of three different crops. RNL, including NH_3 volatilization, NO_3^- leaching, and N_2O emissions, was estimated based on established empirical models [34], expressed as kg N/ha. Reactive nitrogen loss intensity (RNLI), referring to RNL per unit grain yield, was expressed as kg N/kg grain. The GHG emissions consisted of CO_2, and N_2O from farm operations (on-farm emissions) and agrochemical inputs (pro-farm emissions). The on-farm emissions were direct N_2O emissions from the field, which were related to the quantity of N application. The direct N_2O emissions of three crops were estimated based on the experimental model from Cui et al. [34]. The pro-farm emissions were calculated according to Equation (1).

$$GHG_{Pro} = \sum_{i=1}^{n} (I_i \times EF_i) \quad (1)$$

where I_i and EF_i are the amount of each item of input (Table 1) and its coefficient for GHG cost, respectively. The coefficients for the GHG cost are referenced in Table S2. The total GHG emissions were expressed in terms of crop area in kg CO_2 eq/ha, and carbon footprint (CF) was expressed in terms of GHG emissions per kg grain in kg CO_2 eq/kg.

2.6. Comprehensive Assessment

An integrated indicator was calculated per ha to evaluate the overall sustainability performance of different crops using the following equation [38,39]. Four impact factors (NP, EUE, RNL and GHG emissions) in terms of energy, economy, and environmental aspects were involved in the equation.

$$I_{CS} = \sum [W_k (CS_k / R_k)] \quad (2)$$

where I_{CS} is the indicator of different crops; W is the coefficient of weighting; and k represents four factors (NP, EUE, RNL, and GHG emissions). The values of W for NP, EUE, RNL, and GHG emissions are 0.33, 0.33, 0.17, and 0.17 respectively, because economic, energy,

and environmental effects are equally important for assessing sustainable systems [38,39]. CS is the value of the k_{th} impact of different crop systems. R_k is the reference value of kth indicators, which for NP, EUE, RNL, and GHG emissions were 5407 RMB/ha [40], 2.64 [41], 5252 kg CO_2 eq/ha [34] and 47.7 kg N/ha [34], respectively.

The sustainability index (SI) represents the agricultural sustainability in the specific area based on the multiple objectives of AOPST, and SI was also used to evaluate the effectiveness of AOPST. In this study, SI was computed based on the planting area of each crop system in HJH as follows:

$$SI = \frac{\sum(A_j \times I_{csj})}{TA} \quad (3)$$

where SI is the comprehensive index, A is the planting area, I_{CS} is the indicator of the crops calculated from the above formula, j represents different crops, and TA is the total arable area in HJH.

3. Results and Discussion

3.1. Economic Performance

Table 2 shows that the net profit (NP) per ha of wheat, maize, and sunflower were 1118, 1743, and 1849 $/ha, respectively, in 2019. This study showed that sunflower is the most remunerative crop compared to wheat and maize in the arid region, mainly because the price of sunflower (960 $/mg) is higher than wheat (434 $/mg) and maize (232 $/mg). Nevertheless, the economic productivity (PR) (kg/$) of maize was the highest (5.99 kg/$), followed by wheat (3.01 kg/$) and sunflower (1.78 kg/$). However, wheat had the lowest BCR (1.70), while the highest BCR was sunflower (2.13). Table 2 also exhibits the breakdowns of the cost and benefits of these three different crops. For sunflower, human labor represented 28% of the total cost, and fertilizer was 17.5% of the total cost. However, for wheat and maize, fertilizer had the highest ratios of the total cost, which were 27.1% and 24.4%, respectively. Sunflower cultivation consumed 4.4 times more labor than that of wheat and 3.3 times more than that of maize (Table 1). This study also showed that the BCR of each of wheat (1.7) and sunflower (2.13) was significantly higher than that in Turkey (where the BCR of wheat and sunflower were 1.20 and 1.02, respectively) [18]. However, Ghorbani et al. [24] reported that the BCR of wheat in Iran ranged from 1.97 to 2.56, which is higher than our results. This is mainly because the study in Iran did not consider labor costs. In our study, labor costs were addressed, mainly because less and less labor is available in China's rural area.

Economic benefits derived from the sunflower growing area expanded from 19.4 kha in 2015 to 22.1 kha in 2019 in HJH (Table 5). However, with the aggravating trend of an aging population in the rural area and accelerating urbanization, the labor shortage is becoming one of the most important factors impacting farmers' preferences in choosing which crops to grow and is also impacting their field activities [42,43]. The above results indicate that promoting agricultural mechanization and reducing fertilizer application rate are highly required and needed for crop production, and those practices could significantly cut down the cost and improve the net profit for all the crops in the HID [44].

3.2. Energy Performance

The energy inputs and outputs of different crops in HID are presented in Table 3. The highest energy input was 61.2 GJ/ha for maize, followed by wheat (57.6 GJ/ha) and sunflower (40.9 GJ/ha). However, the lowest SE was found for maize (5.94 MJ/kg), wheat (11.96 MJ/kg), and sunflower (14.03 MJ/kg). This study also demonstrated that all three crops consumed significantly higher non-renewable energy (NRE) than renewable energy (RE). The RE of wheat, maize, and sunflower accounted for 20.3, 11.1, and 11.1% of the total energy input, respectively. For wheat, seeds consumed 12.7% of the total energy inputs, while for maize and sunflower, seeds only accounted for 0.9% and 0.4% of the total energy inputs, respectively. The labor energy consumption fraction of total energy input for sunflower (0.8%) was significantly higher than that of wheat (0.2%) and maize (0.2%). The

NRE per ha of wheat, maize, and sunflower were 45.9, 54.4, and 36.3 MJ/ha, respectively. For all three crops, mineral fertilizer was the major contributor, which accounted for 63.4, 64.1, and 62.1% of the total energy inputs, respectively. The total highest energy output per ha was for maize (324.4 GJ/ha), followed by wheat (167.1 GJ/ha) and sunflower (152.2 GJ/ha). Maize also exhibited the highest net energy (NE—263.2 GJ/ha) compared with wheat (109.5 GJ/ha) and sunflower (111.3 GJ/ha). Our study found that the EUE of maize (5.3) was higher than that of wheat (2.90) and sunflower (3.72) in the HID. Although different cereal crops showed varied EUE ranging from 1.41 (wheat) to 12.74 (maize) at different regions, almost all the studies found that maize had higher EUE than wheat [24,45,46]; these results are consistent with our result. Our study also showed that the EUE of sunflower was higher than that of wheat, a finding that is consistent with similar studies in Turkey [18]. Elsoragaby et al. [26] revealed that electricity and fertilizer are the major sources of energy inputs, and electricity was mostly used for pumping water. However, our study found that nitrogen fertilizer, which contributed 56.9% of the total energy inputs in the HID, was the major source of energy inputs. The differences between our study and the findings by Elsoragaby are mainly because the irrigation in the HID area is based on a gravity-fed river system, which does not consume electricity. Kahrl et al. [47] also stated that synthetic nitrogen is the main driver of energy use in China, which is consistent with our study. Our results also found that total energy inputs for wheat (57.6 GJ/ha), maize (61.2 GJ/ha), and sunflower (40.9 GJ/ha) were significantly higher than those of wheat (25.6 GJ/ha) in Turkey [46], maize (23.6 GJ/ha) in Italy [4], and sunflower (31.8 GJ/ha) in Iran [48]. The main reason for these differences between the Chinese and other countries' results also appear to be excessive nitrogen fertilizer use for crops in China. These results suggest that improvement in resource use efficiency, especially with nitrogen fertilizer, would be an important approach to achieve high EUE in the HID.

Table 3. Energy input–output analysis of different crops in the arid region in 2019.

		Wheat		**Maize**		**Sunflower**	
Input	Items	MJ/ha	%	MJ/ha	%	MJ/ha	%
RE	Seed	7413	12.9	558	0.9	159	0.4
	Labor	100	0.2	147	0.2	317	0.8
	Water	3672	6.4	4447	7.3	3570	8.7
	Farmyard manure	523	0.9	1626	2.7	500	1.2
	Subtotal	11,708	20.3	6779	11.1	4547	11.1
NRE	Plastic film	0	0.0	1911	3.1	1782	4.4
	Fertilizers	36,558	63.4	39,263	64.1	25,376	62.1
	Nitrogen (N)	32,465	56.3	35,784	58.5	22,846	55.9
	Phosphorus (P_2O_5)	3683	6.4	3276	5.4	2316	5.7
	Potassium(K_2O)	410	0.7	203	0.3	214	0.5
	Electricity	0	0.0	0	0.0	194	0.5
	Pesticides	428	0.7	501	0.8	594	1.5
	Machinery	2037	3.5	3408	5.6	2867	7.0
	Diesel fuel	6909	12.0	9343	15.3	5532	13.5
	Subtotal	45,932	79.7	54,427	88.9	36,345	88.9
	Total Energy Input	57,640		61,206		40,892	
Output	Main-products	75,799	45.3	170,375	52.5	81,202	53.3
	By-products	91,347	54.7	154,033	47.5	71,029	46.7
	Total Energy Output	167,147		324,408		152,231	
Calculation	NE (MJ/ha)	109,507		263,202		111,339	
	EUE	2.90		5.31		3.72	
	SE (MJ/kg)	11.96		5.94		14.03	

RE: renewable energy; NRE: non-renewable energy; NE: net energy; EUE: energy use efficiency; SE: specific energy.

3.3. Environmental Performance

This study assessed the environmental impacts by calculating RNL and GHG emissions per ha of three different crops in HID, following the method by Chen et al. [37]. The results show that the RNL of wheat, maize, and sunflower were 68.6, 43.6, and 43.2 kg N/ha, respectively (Table 4). The GHG emissions per ha also varied among the different crops in

the arid region. Maize had the highest GHG emissions (6203 kg CO_2-eq/ha), followed by wheat (5004 kg CO_2-eq/ha) and sunflower (3541 kg CO_2-eq/ha). Unlike the RNL, reactive nitrogen loss intensity (RNLI) of sunflower and wheat exhibited a higher value (14.8 and 14.2 kg N/Mg) than maize (4.2 kg N/Mg). Maize also exhibited the lowest carbon footprint (CF 0.60 kg CO_2 eq/kg) compared to wheat (1.04 kg CO_2 eq/kg) and sunflower (1.21 kg CO_2 eq/kg). Pro-farm GHG emissions accounted for around 67.65% of the total GHGs emissions of all three crops. Among the total GHG emissions, fertilizer, especially nitrogen, made the largest contribution to GHG emissions for all three crops in this study.

Table 4. GHG emissions and reactive N loss (RNL) of different crops in the arid region in 2019.

	Item	Wheat	Maize	Sunflower
Pro-farm	Pro-farm emissions (kg CO_2-eq/ha)	4109	4627	2977
	Electricity (kg CO_2-eq/ha)	0	0	18
	Chemical fertilizer			
	Nitrogen (kg CO_2-eq/ha)	2927	3227	2060
	Phosphorus (kg CO_2-eq/ha)	217	193	137
	Potassium (kg CO_2-eq/ha)	25	12	13
	Pesticides (kg CO_2-eq/ha)	80	94	111
	Farmyard manure (kg CO_2-eq/ha)	58	181	56
	Labor (kg CO_2-eq/ha)	6	8	18
	Plastic film (kg CO_2-eq/ha)	0	92	86
	Diesel fuel (kg CO_2-eq/ha)	595	805	477
	Seeds (kg CO_2-eq/ha)	200	15	2
On-farm	On-farm emissions (kg CO_2-eq/ha)	895	1576	564
	RNL (kg N/ha)	68.6	43.6	43.2
	N_2O emissions (kg N/ha)	1.3	3.0	0.8
	NH_3 volatilization (kg N/ha)	28.0	27.1	20.8
	NO_3– leaching (kg N/ha)	39.3	13.5	21.6
	RNLI (kg N/Mg)	14.2	4.2	14.8
Total	GHG emissions (kg CO_2-eq/ha)	5004	6203	3541
	CF (kg CO_2-eq/kg)	1.04	0.60	1.21

RNL: reactive nitrogen losses; RNLI: reactive nitrogen losses intensity; GHG: greenhouse gas; CF: carbon footprint.

Our study found that the RNL of wheat, maize, and sunflower were different in the HID. Although more N fertilizer had been applied for maize than wheat in the study area, RNL of wheat was higher than maize. This is mainly because more N is required for maize production than wheat production (Table 2), and nitrogen leaching in the wheat system is higher than maize (Table 4). These results are consistent with the findings by Zhang et al. [49], who also reported that N loss of the wheat production system was higher than the maize production system at the global level. In our study, the N inputs by farmers were around 2.0–2.5 times the crops' required amount, which resulted in large N losses. Ju et al. [9] also stated that the current agricultural N inputs by farmers for wheat and maize production in the North China Plain were leading to about two times larger N losses to the environment when compared with knowledge-based optimum fertilization.

The GHG emissions of different crops in the HID varied from 3541 to 6203 kg CO_2 eq/ha, which were in the range of observations in China from 2203 to 15,465 kg CO_2 eq/ha [37]. In other reports, the GHG emissions of crops in Germany ranged from 452 to 3505 kg CO_2 eq/ha [50]. Babu et al. [51] reported that GHG emissions of crops in India varied from 1250 to 2120 kg CO_2 eq/ha. However, the GHG emissions in our study were far higher than those in other countries [52]. Higher nitrogen inputs by farmers in the HID were the major reason that results in the greater GHG emissions compared to other countries. Our study also observed that N fertilizer was the most important factor governing the GHGs emissions in the HID; this finding is consistent with other reports in China [53–55]. Therefore, optimizing fertilizer might be essential to reduce the environmental risk and to realize the aim of low RNL and GHG emissions in the HID.

3.4. Comprehensive Performance

Meeting the food requirements of a growing global population and achieving increased economic development concurrently without deteriorating environmental degradation quality and with less non-renewable energy consumption for world sustainable development is the major challenge for researchers and policymakers in the world [17,56–58]. However, many challenges have been addressed singly [59], such as agronomists concentrating on food production, environmental protectors paying attention to environmental degradation, and the national security sector addressing energy reserves. However, reducing one problem while exacerbating others cannot meet the multiple objectives of current societal demands [17,56–58]. Recent quantitative studies have addressed the comprehensive evaluation of sustainability of agricultural systems. Our study chose the four impact factors (NP, EUE, RNL, and GHG emissions) to evaluate the overall performance of different crops in terms of energy, economy, and environmental aspects. Gómez-Limón and Sanchez-Fernandez [57] selected 16 sustainability indicators that cover economic, social, and environmental aspects to analyze the sustainability of farms in Spain. Yan et al. [60] evaluated different agricultural production systems by using energy, carbon, and economic indicators in China. Bos et al. [61] used energy and GHG emissions to assess the organic and conventional farming systems in the Netherlands. Comprehensive assessment is becoming a useful and valuable tool for relevant stakeholders to better understand the overall performances of systems [62], and the evaluation results could provide useful reference information for integrated decision making [54,63,64]. Our study evaluated the GHG as one of the environmental indicators, mainly because reducing the GHG emissions from the food production system has always been considered as the priority objective of Chinese sustainable development [28,65–67]. Additionally, RNL, including NH_3 volatilization, NO_3^- leaching, and N_2O emissions has been considered as another environmental factor which also could indirectly reflect a broad range of environmental aspects, such as NH_3-caused air pollution [68], and NO_3^- leaching that results in soil acidification and eutrophication [69].

The results showed that the different crops performed diversely in terms of energy, economy, and environmental aspects. Sunflower had the best economic performance compared to wheat and maize, while from the energy aspect (EUE), maize performed better than wheat and sunflower (Table 5). From the environment aspects, wheat had the highest RNL, and the highest GHG emissions were found in maize. The overall performance (I_{CS}) varied among different crops in the HID. Maize had better overall performance (I_{CS} = 0.71) in comparison with wheat (I_{CS} = 0.22) and sunflower (I_{CS} = 0.63) (Table 5). These results indicated that AOPST might be an effective approach to enhance the overall agricultural efficiency and to achieve sustainable development in the HID. However, the AOPST program did not implement well in HJH. Although maize was encouraged by the government in the HID by increasing a maize subsidy (245 $/ha) compared to wheat (166 $/ha) and sunflower (166 $/ha) (Table 5), the maize sowing area decreased from 38.0 kha in 2015 (before implementing the AOPST program) to 29.4 kha in 2019, which resulted in the sustainability index (SI) of HJH decreasing from 0.50 in 2015 to 0.44 in 2019. Several reasons could explain this phenomenon. Firstly, more services (agricultural machinery cooperatives supply technicians and professional equipment to smallholder farmers) are required by maize than by the other two crops (Table 1), which results in higher costs when comparing to wheat and sunflower. Farmers growing maize highly rely on these services. However, at harvest time, the demand for professional services increases, and not all the farmers can get the services on time. Secondly, maize is not the most profitable crop compared to sunflower and costs more in labor as compared to wheat. Last but not least, the sale price of maize in the last decade had larger fluctuations (CV is 13.8%) than wheat (CV is 8.2%) and sunflower (CV is 9.7%) [40].

Table 5. Comprehensive assessment of different crop systems in the arid region.

	Wheat	Maize	Sunflower	Reference	Weight
NP ($/ha)	1118	1743	1849	1411	0.33
EUE	2.90	5.31	3.72	2.64	0.33
RNL (kg N/ha)	68.6	43.6	43.2	47.7	−0.17
GHG emission (kg CO_2-eq/ha)	5004	6204	3541	5252	−0.17
I_{CS}	0.22	0.71	0.63		
	Wheat	Maize	Sunflower	Total sowing area	SI
Sowing area (kha) in 2015	20.4	38.0	19.4	88.14	0.50
Sowing area (kha) in 2019	25.9	29.4	22.1	91.57	0.44

NP: net profit; RNL: reactive nitrogen losses; NE: net energy; GHG: greenhouse gas; I_{CS}: crop indicator; SI: sustainability index.

3.5. Scenario Analysis

The above results showed that mineral fertilizer, especially nitrogen, was the dominant factor affecting the overall performances of different crops in the HID. Labor is another factor, which influenced the economic performance of crops, especially for sunflower. The results from 454 field experiments in the HID conducted by a local agricultural extension center showed that there is great potential for farmers to increase those three crop yields by using the optimal amount of fertilizers (Figure S1). Farmers in the HID overused N and P fertilizer around 2.0–2.5 times more than crop requirements. Ju and Gu [70] reported that a 30% reduction in N fertilizer application would not impact the crop yield in China. Therefore, we conducted three scenarios (S1–3) related to field management of different crops (Table 6). S1—Labor reduction: all the field manual work was replaced by machine for all the crops without changes to other factors; S2—Fertilizer −30%: reduce 30% of nitrogen N and P application rates based on the current fertilizer application rate, but keep crop yields the same. S3—optimal fertilizer management: optimal fertilizer rates and yield from the recorded field experiments were applied (Figure S1). The comprehensive assessment showed that maize had the best overall performance compared to wheat and sunflower. We made another two scenarios (S4 and S5) related to land-use changes (Table 6). S4—AOPST: increase 20% of the maize area without changing other crops' sowing areas, and without changing the field management. S5—AOPST and optimal: increasing the maize sowing area by around 20% and simultaneously adopt optimal fertilizer management (same as S3 management). These five scenarios were set to assess the impact of different improvement opportunities on SI in terms of economic, energy, and environmental aspects. The results showed that compared to current field management, improving field management (S1–3) and adjusting the planting structure (S4,5) could all improve the SI of HJH. The SI increased from the current value of 0.44 to 0.54 when the maize growing area increased by 20% (S4); this change was significantly smaller than S3, the SI of which increased 118.5%. Different field management techniques would improve the overall performance of crops differently (Table 6). The effect of reducing the manual labor (S1) on the overall performance of sunflower (Ics increases 17.7%) was higher than that of wheat (Ics increases 11.2%) and maize (Ics increases 4.8%). Reducing 30% of nitrogen and phosphorous fertilizer based on the current fertilizer rate (S2) was more effective for wheat (Ics increases 112.2%) than maize (Ics increases 39.4%) and sunflower (Ics increases 31.2%). Optimal field management with increasing crop yield (S3) could significantly improve the overall performance of all crops (I_{CS} for wheat, maize, and sunflower increased 221.7%, 111.8%, and 86.7%, respectively). After undertaking the optimal field management and adjusting the planting structure (S5), the SI value could improve around 161.6%. These scenario analyses also indicated that encouraging farmers to shift their habits of using huge amounts of fertilizer, especially nitrogen, to the optimal rate would be a more effective approach than adjusting the planting structure in the HID to achieve the objectives of AOPST.

Table 6. Scenario analysis.

	Wheat		Maize		Sunflower		HJH	
	I_{CS}	Changes (%)	I_{CS}	Changes (%)	I_{CS}	Changes (%)	SI	Changes (%)
Current	0.22		0.71		0.63		0.44	
S1—Labor reduction	0.24	11.2	0.75	4.8	0.74	17.7	0.49	10.1
S2—Fertilizer (−30%)	0.46	112.2	1.00	39.4	0.83	31.2	0.65	46.7
S3—Optimal	0.70	221.7	1.51	111.8	1.17	86.7	0.97	118.5
S4—AOPST	0.22	0.0	0.71	0.0	0.63	0.0	0.54	21.4
S5—AOPST-optimal	0.70	221.7	1.51	111.8	1.17	86.7	1.16	161.6

3.6. Significance for Relevant Stakeholders

This study conducted a survey approach to quantify agricultural sustainability based on the multiple objectives of AOPST in the arid region with irrigation conditions and proved that AOPST is a potential approach to achieve multiple objectives for sustainable development in the HID. The concept of evaluating agricultural program effectiveness from multiple dimensions could be widely used for future decision-making at the global agricultural governance and management level. In the HID, economic, energy, and environmental aspects were considered equally important, and the weights of those aspects for SI calculation were even distributed. However, in some regions close to the metropolitan area, alleviating environmental degradation and energy consumption pressure might be the primary objectives, while in some economically underdeveloped areas, achieving higher yield and economic income might be prioritized. In these situation, different weights could be given based on the importance of the objectives of different regions [38].

This study was conducted in the HID through in-person surveys, which reflected actual crop production processes by farmers. The results show that there are huge gaps of crop yield and fertilizer application rates between the field management of farmers and the optimal management values recorded by the researchers' experiments. Engaging farmers to adopt scientific fertilizer application techniques is urgently needed in this region. Cui et al. [34] reported the possibility of engaging millions of Chinese smallholder farmers to adopt enhanced management practices for greater yield and environmental performance at the national level. Therefore, this study suggests the current agricultural-extension system in the HID should revert its role from promoting fertilizer sales to assisting farmers in using fertilizer rationally. This suggestion has also been recommended by Gong et al. [8] at the national level.

The goals of reducing the fertilizer application rate without changing production have been provided as possibilities in many studies in China by enhancing the fertilizer application techniques [10,34,37,71]. Compared to the implementation of the AOPST, stimulation of advanced fertilizer application techniques is suggested for local policy makers. More attention should be paid to encourage the farmer to adopt advanced field management practices.

3.7. Caveats of the Estimation

(1) In the present study, we compared the economic performance of three crops using NP, BCR, and PR indicators, which are commonly used in the studies. However, as those indicators are sensitive to the market price of the products, marginal analysis of the products needs to be considered in the future.

(2) Mulching of soil can reduce water loss through evaporations and increase the soil surface temperature. Plastic film mulching has been widely used for maize and sunflower production, and it has become a valuable technique for increasing grain production in arid and semiarid areas, including the HID. However, plastic film pollution has been a serious issue for agricultural sustainable development in China. The main problems are residues left in the soil that destroy soil structure, affect soil permeability, and block crop root system development. Our study focused on GHG emissions and RNL, which have been commonly used for environmental assessment at the national level. For further studies, especially in the north and the northwest of

China (arid and semiarid regions), considering the impact of plastic film is becoming an imperative indicator to comprehensively evaluate agricultural sustainability.

(3) In the process of a comprehensive assessment of agricultural sustainability with multi-dimensional aspects, selecting indicators, designing the weighting of those indicators, and choosing the reference values all might influence the final score. In this study, to make an integrated assessment of different crops, the weights of three aspects (economic, energy, and environmental) were conducted with equal importance to agricultural sustainability. However, in other region or places, indicators and their weights need to be adjusted based on the objectives of the program and the importance of the objectives.

4. Conclusions

The present study for the first time demonstrated the effects of different crops on agricultural sustainability in terms of economic, energy, and environmental aspects in the largest designed irrigation area in China. Sunflower exhibited the best economic and environmental performance, while maize showed the best energy and overall performance in the HID. This study also provides a comprehensive assessment method to evaluate the sustainability and effectiveness of the agricultural program APOST. The present results showed that AOPST (expanding maize area) is useful, but not the most effective approach to improve the agricultural sustainability in the HID. Improving farmers' field management by optimizing fertilizer application rates is the most effective strategy to enhance agricultural sustainability. Therefore, policy-makers, agricultural-extension advisers, sellers of fertilizer, and researchers should pay more attention to helping farmers to improving their skills, especially fertilizer application skills. In addition, preliminary soil analysis to assist farmers to define a precise fertilization plan should be addressed in this area.

Supplementary Materials: The following are available online at https://www.mdpi.com/2071-1050/13/1/342/s1, Table S1: Energy equivalents for agricultural inputs and outputs of different crop production systems, Table S2: Emission factors of agricultural inputs.

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