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Article

Towards Greener Watermelon Production in China: From Regional Assessments to Field Optimization

Huanyu Zhao ^{1,2}, Yujia Li ^{2,3,†}, Yuheng Wang ^{2,4}, Jiawei Xie ^{2,4}, Yu Xu ¹, Deshui Tan ^{1,*} and Yueqiang Zhang ^{2,4,5,*}

¹ State Key Laboratory of Nutrient Use and Management, Institute of Agricultural Resources and Environment, Shandong Academy of Agricultural Sciences, Jinan 250100, China

² College of Resources and Environment, Southwest University, Chongqing 400716, China

³ Ecological Environment Monitoring Station of Hechuan District, Chongqing 401519, China

⁴ Interdisciplinary Research Center for Agriculture Green Development in Yangtze River Basin, College of Resources and Environment, Southwest University, Chongqing 400716, China

⁵ National Monitoring Station of Soil Fertility and Fertilizer Efficiency on Purple Soils, Chongqing, 400716, China

* Correspondence: tandeshui@163.com (D.T.); zhangyq82@swu.edu.cn (Y.Z.)

† This author contributed equally to this work.

Abstract

The global consumption of resources and environmental problems are becoming increasingly serious. China produces 61.0% of the world's watermelons, yet no comprehensive assessment of the resource consumption and environmental effects of China's watermelon production system has been reported. This study applies life cycle assessment (LCA), combining farmer surveys with field experiments, to systematically evaluate and verify the reduction potential of land occupation (LO), water depletion (WD), energy depletion (ED), global warming potential (GHG), acidification potential (AP), and eutrophication potential (EP), as well as the resource budget and environmental impact index (REI), in north China (NC), northwest China (NW), and southwest China (SW). The results reveal significant differences in resource consumption and environmental effects. The NC region was found to achieve the highest yield, 146% and 174% greater than the two other regions, but also to exhibit the highest resource use and emissions per unit area, with the lowest REI. By contrast, the SW region was found to achieve the most favorable performance in resource consumption and environmental emissions per unit yield. During the material stage (MS), more than 86.6% of energy and water resources are consumed, while in the farm stage (FS), 47.3% to 98.7% of total pollutants are emitted. Nitrogen (N) fertilizer is identified as the main contributor to GHG, WD, and EP, with field application accounting for more than 85% of the total impact. Although REI values across the three regions remain low, yield management and improved N fertilizer efficiency (PFP_N) present a reduction potential of 46.5% to 55.4%, enabling both high yield and high efficiency. Field experiments further verify that reducing N fertilizer use by 14.3% to 40.0% can lower environmental impacts, which is of great significance for promoting green watermelon production.

Keywords: watermelon; life cycle assessment; resource consumption and environmental effects; mitigation potential; green watermelon production

1. Introduction

The massive consumption of resources and the continuous deterioration of the environment are two major ecological problems worldwide. At present, the global population is steadily growing, and food demand continues to increase. Meanwhile, the inputs of water, fertilizer, and other resources in agricultural production are also rising [1]. It is estimated that by 2050, to meet global food demand, agricultural resource input must increase by more than 50% [2]. However, the efficiency of resource

utilization remains generally low, which has exerted a serious impact on the environment [3]. Excessive input of agricultural materials has generated large amounts of greenhouse gas (GHG) emissions, with an even stronger impact observed for economic crops such as orchards and vegetables [4–6]. Therefore, in the face of ever-growing human demands, the agricultural production system faces severe challenges: to pursue output growth while simultaneously improving resource use efficiency and reducing environmental emissions [7,8]. The problem of excessive resource input in agricultural production and the resulting environmental consequences have received increasing attention from agricultural researchers.

In agricultural systems, nitrogen (N) input plays a crucial role and continues to increase [9], placing considerable pressure on global resources and the environment. Within the planetary boundary framework for Earth system sustainability, the biogeochemical cycle of N has already far exceeded the safe boundary [10]. The environmental impacts caused by N fertilizer input are greatest in multiple crop systems, including food crops [11], orchards, and vegetables [4,6]. Excessive application of N fertilizer not only fails to enhance crop yields but also leads to leaching losses in areas with high precipitation, improper irrigation, or poor soil fertility, thereby contaminating groundwater and surrounding rivers or lakes [12–14]. In addition, it causes large GHG emissions through volatilization [15,16].

Life cycle assessment (LCA) is a method used to quantify the environmental load of agricultural production from cradle to farm. By evaluating both the agricultural input stage and the farming stage of crop production, LCA analyzes the environmental impact throughout the entire production process [17]. Assessments of different crops using the LCA method have also shown that the emissions generated during N fertilizer production cannot be ignored [18]. Therefore, clarifying the scientific management of N fertilizer in crop production systems with different management models is of particular importance.

With the continuous growth of the global population and economic development, human demands are also steadily increasing. Therefore, while ensuring food security, improvement of the production of fruits and vegetables is an important guarantee for the daily nutrition supply of human beings [19]. Watermelon, as an important summer fruit, is not only rich in nutrients and flavor, but its by-products also contain abundant vitamins, minerals, and bioactive compounds that benefit cardiovascular health, diabetes management, and gastrointestinal health [20]. In 2023, the global planting area of watermelon reached 3.04 million hectares (Mha), with a total production of 64 million tons (Mt). Among these, China accounted for 49.1% of the global planting area and 61.0% of total production [9]. Khoshnevisan et al. assessed watermelon cultivation in Iran, reporting average GHG emissions of 9,485.47 kg CO₂-eq ha⁻¹ yr⁻¹, with electricity use as the largest contributor [21]. As Iran is an inland arid region, irrigation requires substantial electricity input. By contrast, the situation of the watermelon cultivation system in China remains unclear. Clarifying the resource input and environmental impact of China's watermelon cultivation system is therefore essential for understanding the scientific management of watermelon production worldwide.

This study evaluates the resource consumption and environmental emissions of watermelon production in China using the LCA method, and quantifies the potential for resource conservation and emission reduction under price-adjusted optimization measures across different regions. This study aims to: (1) develop a deeper understanding of the regional characteristics of watermelon production in China and identify advantageous production areas; (2) examine the resource consumption and environmental effects of watermelon production and determine the key factors influencing environmental outcomes; and (3) identify high-productivity practices under optimized production conditions in different regions, explore the optimization potential of different regions, and provide a scientific basis for the sustainable production and full-process optimized management of watermelon production in China.

2. Materials and Methods

2.1. Study Region

Based on previous studies, watermelon production in China can be divided into six typical regions (Figure 1): the northeast cultivation region (NE), the north China large-scale variety cultivation region (NC), the northwest dry climate cultivation region (NW), the southwest wet cultivation region (SW), the Yangtze River rainy cultivation region (YZ), and the south China multi-cropping region (SC). Among these, NC, NW, and SW together accounted for 52.2% of the national planting area and 58.7% of total yield in 2018 [22], and were regarded as the most important watermelon-producing regions, especially in summer. In terms of production ranking, NC, NW, and SW respectively placed first, third, and sixth, representing the highest, medium, and lowest levels nationwide. In addition to differences in production scale and supply characteristics, yields in the three regions vary greatly due to differences in climate, soil texture, variety, irrigation and fertilization management, farmers' practices, and farm size (Table S1).

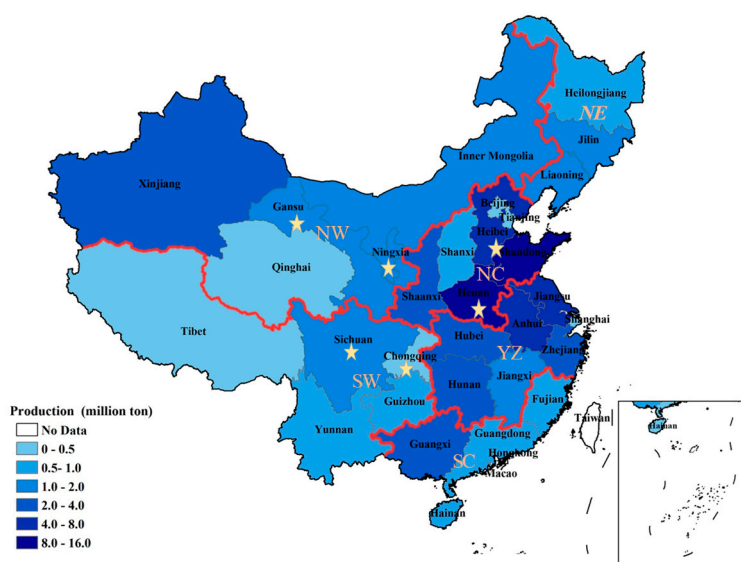


Figure 1. The distribution of watermelon production in different provinces of various regions of China.. China was divided into six regions, northeast cultivation region(NE), north China large-scale variety cultivation region(NC), northwest dry climate cultivation region(NW), southwest wet cultivation region(SW), the rainy weather of the Yangtze river cultivation region(YZ) and south China multi-cropping region(SC), respectively by the red lines. Well, the provinces surveyed were identified by a symbol resembling a pentagram.

2.2. Data Sources

From 2019 to 2020, a detailed farmer survey was conducted in six provinces across three regions: NC (Henan, Hebei), NW (Gansu, Ningxia), and SW (Sichuan, Chongqing) (Figure 1). Following the farmer survey method described by Jia et al. [23], two provinces or municipalities were randomly selected within each region, and three towns were randomly selected in each province or municipality for investigation. Questionnaires were distributed only to farms with a planting area larger than 0.13 ha. All materials from preparation to harvest were recorded in detail, including fertilizer, pesticide, agricultural plastic film, fuel oil, and irrigation use in watermelon production. Based on the proportion of sample numbers and planting scales within each cultivation region, a total of 295 valid data points were obtained after excluding outliers. These data served as the primary input for LCA analysis. The investigated inputs and outputs for the LCA of watermelon production across the three regions were compiled in Excel 2010 and are presented in Table 2.

In addition, field experiments were conducted to verify the potential of optimizing N management for resource conservation and emission reduction. Indicators and parameters obtained in the field stage were consistent with those collected through the survey.

2.3. System Boundary

2.3.1. Scope Definition

In accordance with the LCA principles and framework proposed by ISO14040 [17], the LCA methodology was applied to evaluate the potential environmental impacts and resource consumption of watermelon production from cradle to farm. The system boundary extended from raw material extraction for watermelon production to fruit harvest (Figure 2). The sustainability influence of agriculture can be divided into two main categories: resource utilization and environmental influence. In this study, resource utilization focused on land occupation (LO), water depletion (WD), and energy depletion (ED), while environmental impact included global warming potential (GHG), acidification potential (AP), and eutrophication potential (EP). Furthermore, the production system was divided into the agricultural materials stage (MS), which included the production processes of fertilizer, pesticides, agricultural plastic films, and diesel, and the arable farming stage (FS), which covered the entire process of crop cultivation in the field [24]. The land, water, and energy consumed in the production of plant equipment, construction facilities, and transportation equipment in the MS were excluded from the life cycle inventory (LCI) due to a lack of available information.

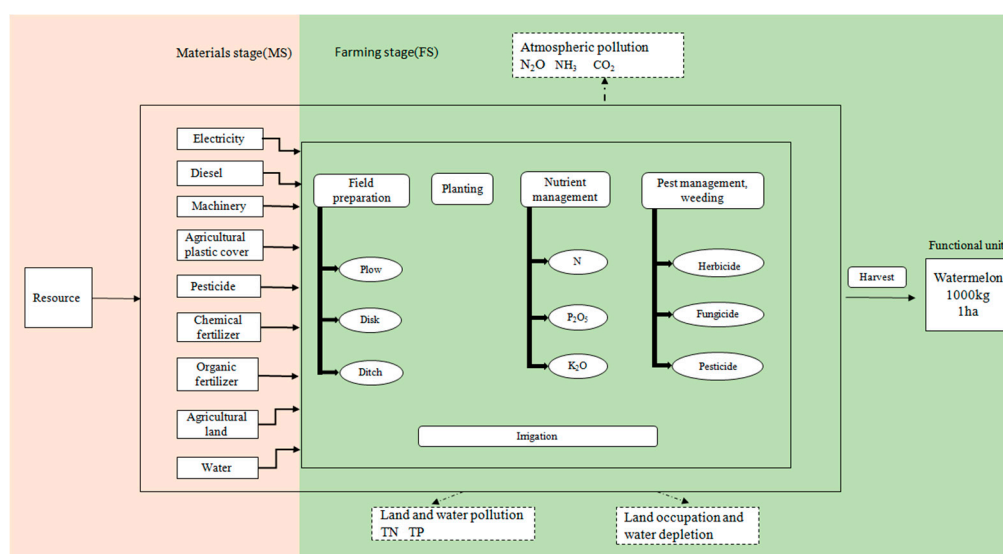


Figure 2. System boundary for watermelon production in China. In this system, it was divided into the agricultural materials stage (MS), which was the pink part and the arable farming stage (FS) made up of green.

In this study, one ton (per t) of watermelon was taken as the main functional unit. Because differences in environmental effects under different cultivation conditions and sequences depend on the choice of functional units [25], yield per hectare (per ha) was also considered as an auxiliary unit to better reflect environmental burdens and agricultural productivity in different cultivation regions during the characterization phase.

2.3.2. Data Analysis

Resource consumption and pollutant emissions associated with the production of fertilizer and other raw materials, as well as emissions during the FS of watermelon production, are presented in Tables S2 and S3, respectively. LO was evaluated using net primary productivity multiplied by the land use coefficient [26]. WD per functional unit ($\text{m}^3 \text{unit}^{-1}$) was calculated according to Eq. (1). ED in

the FS considered only electricity and irrigation, according to Eq. (2), with corresponding parameters of 12.5 MJ kWh⁻¹ and 4.95 MJ m⁻³, respectively. The potentials of LO, WD, and ED under both functional units were compared using the Kruskal–Wallis one-way analysis of variance (ANOVA) for independent samples in SPSS (20.0 version) to account for non-normal distributions, and the results are presented in Figure 4.

For environmental characterization, GHG, AP, and EP were calculated following IPCC [27] and Hauschild and Wenzel [28]. Contaminants such as ammonia (NH₃), nitrate (NO₃), and nitrous oxide (N₂O) were converted into carbon dioxide (CO₂), sulfur dioxide (SO₂), and phosphorus tetroxide (PO₄), respectively, based on Wang et al. [29] (Eq. (3)). The calculation process is as follows:

$$F_w = \sum Q_{W(ip)}, \quad (1)$$

where F_w represents the amount of WD (m³ per unit⁻¹), and $Q_{W(ip)}$ represents the WD of the i -th application in phase p .

$$F_E = \sum Q_{E(ip)}, \quad (2)$$

where F_E represents the amount of ED (MJ per unit⁻¹), and $Q_{E(ip)}$ represents the ED of the i -th application in phase p .

$$EI_j = \sum_{i=1}^n (P_{FSij} \div P_{MSij}) \times rate_i, \quad (3)$$

where EI_j represents the potential for the j -th impact category; j (1, 2, 3) corresponds to global warming (kg CO₂-eq per unit⁻¹), acidification (kg SO₂-eq per unit⁻¹), and eutrophication (kg PO₄-eq per unit⁻¹); $rate_i$ represents the application rate of watermelon growth inputs, including N, P₂O₅, K₂O, pesticides, diesel, and plastic film; P_{MSij} represents the emission potential of the j -th impact category per kilogram of i input produced and transported; and P_{FSij} represents the emission potential of the j -th impact category per kilogram of i input applied. Furthermore, MS refers to the agricultural materials stage, and FS refers to the arable farming stage.

2.3.3. Impact Assessment

By weighting different types of resource consumption and environmental effects, the relative importance of each output in the watermelon production system was determined. To achieve this, the concept of the resource and environment impact index (REI) is introduced. In the normalization step, each environmental impact potential was divided by the world per-capita environmental impact normalization factor for 2005, to calculate an environmental index applicable to both organic and conventional production systems. In the weighting phase, each normalized indicator value was multiplied by a weighting factor (Table S4), as described by Liang et al. [26]. Finally, a comprehensive index of resource budget and environmental impact was obtained for comparison among the different environmental categories:

$$REI = \sum_{j=1}^n EI_j \div SRV_j \times EC_j, \quad (4)$$

where REI represents the comprehensive ecological index; j (1, 2, 3, 4, 5, 6) corresponds to LO (m² t⁻¹), WD (m³ t⁻¹), ED (MJ t⁻¹), GHG (kg CO₂-eq t⁻¹), AP (kg SO₂-eq t⁻¹), and EP (kg PO₄-eq t⁻¹); EI_j represents the impact value of category j ; SRV_j represents the standardized reference value for category j (unit person⁻¹ a⁻¹); and EC_j represents the weight coefficient of the j -th category.

2.4. Optimization Potential Analysis

The relationship between input-output performance and resource and environmental costs within the same cultivation region was compared using the grouping method of Ye et al. [30]. On this basis, optimization potential was evaluated. The N fertilizer efficiency (PFP_N) was taken as a key indicator for assessing fertilizer efficiency in agricultural production [31]. The survey data from the three regions were divided into four groups according to average yield and average PFP_N (Eq. (5)): low yield and low PFP_N (LL); low yield and high PFP_N (LH); high yield and low PFP_N (HL); and high yield and high PFP_N (HH) [32]. To quantitatively evaluate the contribution of nutrient management practices to watermelon yield, as well as their effects on resource use and environmental impact indexes across regions, mitigation potential was ultimately assessed.

$$PPFN = Y / N_{input}, \quad (5)$$

where $PPFN$ represents N partial factor productivity (kg kg^{-1}); Y represents yield per unit area after fertilization (t ha^{-1}); and N_{input} represents the input of N fertilizer (t ha^{-1}).

2.4. On-Farm Trial

In 2021, a total of seven fertilizer optimization experiments were conducted, including five in NC and two in SW. The geographical locations and cultivation practices of the experimental field were consistent with those of the surveyed areas. Each site included three treatments: farmer practice (FP), optimal N (OPT), and optimization with no N (OPT-N). The FP treatment represented the fertilization practices used by local farmers. The OPT treatment was calculated by multiplying the target yield by the nutrient absorption per unit yield. For OPT and OPT-N, the application rates of phosphorus (P) and potassium (K) fertilizers were the same, but N fertilizer was omitted entirely in OPT-N. Specific fertilization dosages are provided in Table 3. At each site, input and output data were recorded, and the potential environmental cost values of the six resource and environmental indicators were calculated.

3. Results

3.1. Regional Differences in Agricultural Input and Yield Effects for Watermelon Production in China

Survey results from the three watermelon production regions in China showed that the average total inputs of N, P, and K were 397 kg N ha^{-1} , $282 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$, and $399 \text{ kg K}_2\text{O ha}^{-1}$, respectively. The average inputs of pesticides, diesel, plastic film, irrigation water, and electricity were 3.92 kg ha^{-1} , 23.7 L ha^{-1} , 333 kg ha^{-1} , $47.0 \text{ m}^3 \text{ ha}^{-1}$, and 237 kWh ha^{-1} , respectively. The national average yield was 42.9 t ha^{-1} (Table 1).

Significant differences in nutrient inputs were observed among the regions. Inputs in NC were the highest, with N, P, and K levels of 558 kg N ha^{-1} , $383 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$, and $572 \text{ kg K}_2\text{O ha}^{-1}$, which were respectively 270%, 233%, and 561% higher than those in NW (Table 1). Other agricultural inputs were also the highest in NC. Notably, mechanical input is almost absent in NW, while irrigation in SW relies mainly on rainfall. The yield in NC was the highest at 56.8 t ha^{-1} , which was 174% higher than that in SW (Table 1). Moreover, an analysis of $PPFN$ in the three regions showed that the proportion of HH farms was 31.1%, 12.5%, and 15.0% in NC, NW, and SW, respectively (Figure 3).

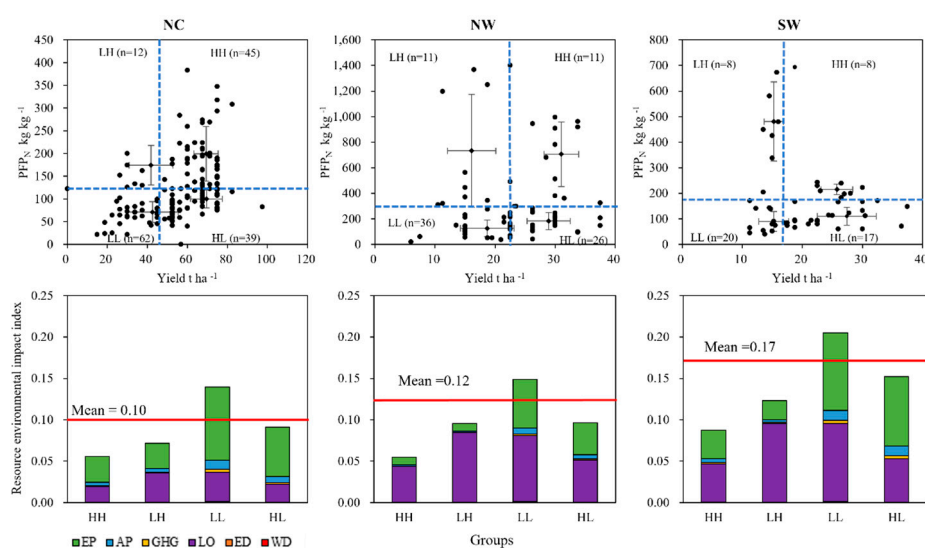


Figure 3. The relationships among yields and PFPN of watermelon production among four groups in NC, NW, SW. The groups LL, LH, HL, and HH were distinguished. The cross intersection was the group mean and values

were means \pm SD. (d) (e) (f) were comparison of resource environmental impact index and optimization potential under different groups corresponded to (a) (b) (c). The red line represented the region average REI.

Table 1. Inputs and outputs of producing watermelon in China.

Input and output	North China (n=158)	Northwest (n=84)	Southwest (n=53)	Nation (n=295)
Total fertilizer (kg ha⁻¹)				
N	558 \pm 256	151 \pm 120	208 \pm 177	397 \pm 282
P ₂ O ₅	383 \pm 245	115 \pm 95.0	183 \pm 134	282 \pm 236
K ₂ O	572 \pm 266	86.5 \pm 75.4	285 \pm 177	399 \pm 313
Organic fertilizer (kg ha⁻¹)				
N	387 \pm 202	73.0 \pm 40.5	67.5 \pm 38.2	256 \pm 221
P ₂ O ₅	235 \pm 131	25.0 \pm 13.8	114 \pm 80.0	157 \pm 148
K ₂ O	363 \pm 178	51.6 \pm 35.2	153 \pm 88.0	246 \pm 210
Chemical fertilizer (kg ha⁻¹)				
N	171 \pm 106	78.3 \pm 65.2	140 \pm 79.0	142 \pm 105
P ₂ O ₅	148 \pm 127	90.1 \pm 43.6	69.6 \pm 46.5	125 \pm 113
K ₂ O	209 \pm 118	34.9 \pm 24.1	132 \pm 106	153 \pm 134
Pesticide (kg ha ⁻¹)	4.38 \pm 2.59	2.33 \pm 1.17	3.00 \pm 0.80	3.92 \pm 5.79
Diesel (L ha ⁻¹)	37.1 \pm 18.4	0.00 \pm 0.00	27.9 \pm 2.80	23.7 \pm 21.3
Plastic film (kg ha ⁻¹)	512 \pm 341	102 \pm 11.0	84.8 \pm 18.6	333 \pm 329
Irrigation (m ³ ha ⁻¹)	70.6 \pm 11.6	23.6 \pm 21.8	0.00 \pm 0.00	47.0 \pm 31.7
Electricity (Kwh ha ⁻¹)	341 \pm 219	106 \pm 81.0	0.00 \pm 0.00	237 \pm 234
Yield (t ha ⁻¹)	56.8 \pm 16.4	23.1 \pm 6.80	20.7 \pm 11.1	42.9 \pm 21.0

The cross intersection was the group mean and values were means \pm SD.

Table 2. The environmental impact of watermelon production in three regions.

		NC			NW			SW		
		MS	FS	Total	MS	FS	Total	MS	FS	Total
Per t of the watermelon										
Global warming	kg CO ₂ -	37.0	84.4	121	39.2	48.1	87.3	79.5	71.3	151
Acidification	kg SO ₂ -eq	0.11	2.90	3.01	0.11	1.86	1.97	0.22	3.10	3.32
Eutrophication	kg PO ₄ -	0.01	0.97	0.99	0.01	0.63	0.64	0.03	1.07	1.09
Per ha of the watermelon										
Global warming	kg CO ₂ -	1786	4323	6109	795	1040	1835	1359	1257	2616
Acidification	kg SO ₂ -eq	5.24	148	153	2.21	39.6	41.8	3.79	54.2	58.0
Eutrophication	Kg PO ₄ -	0.60	49.6	50.2	0.26	13.4	13.6	0.45	18.6	19.1

Table 3. Field verification results in NC and SW.

Reg	Nu	Treat	Total			Yie	PFP-N	Impact category (t ⁻¹)						RE
			N	P ₂	K ₂			ld	(kg kg ⁻¹)	LO	W	ED	GHG	
NC	18H B01	OPT-	0	95	30	50.	-	200	5.0	581	23c	0.23c	0.03c	0.0
		OPT	2	95	30	66.	253a	150	8.1	673	68b	1.27b	0.37b	0.0
		FP	5	39	48	62.	119b	161	10.	680	105a	2.4a	0.77a	0.0

18H B02	OPT-	0	95	30	54.	-	185	4.6	284	21b	0.21b	0.02b	0.0
	OPT	2	95	30	62.	215a	161	9.1	480	77a	1.46a	0.43a	0.0
	FP	4	15	38	61.	150a	163	12.	609	104a	2.03a	0.62a	0.0
18H N01	OPT-	0	63	20	39.	-	253	3.8	305	18b	0.18b	0.01b	0.0
	OPT	1	63	20	46.	268a	215	7.3	448	63ab	1.19b	0.35b	0.0
	FP	3	35	35	40.	108b	246	17.	613	122a	2.66a	0.85a	0.1
18H N02	OPT-	0	63	20	45.	-	221	3.3	267	16c	0.16c	0.01c	0.0
	OPT	1	63	20	46.	270a	213	7.3	445	63b	1.18b	0.34b	0.0
	FP	3	33	34	46a	124b	217	14.	527	105a	2.3a	0.73a	0.0
18H N03	OPT-	0	63	20	60.	-	167	2.5	201	12c	0.12c	0.01c	0.0
	OPT	1	63	20	69.	400a	144	4.9	300	42b	0.79b	0.23b	0.0
	FP	3	33	34	63.	172b	157	10.	380	76a	1.66a	0.53a	0.0
SW 18C Q01	OPT-	0	12	24	15.	-	641	15.	193	48c	0.42c	0.05c	0.1
	OPT	1	12	24	26.	179a	372	15.	140	99b	1.79b	0.53b	0.1
	FP	2	19	26	26.	108a	385	19.	153	139a	2.78a	0.86a	0.1
SW 18C Q02	OPT-	0	12	24	19.	-	521	11.	456	21c	0.12c	0.03c	0.0
	OPT	1	12	24	27.	184a	363	13.	592	84b	1.59b	0.51b	0.0
	FP	2	17	28	26.	101b	380	18.	750	134a	2.79a	0.91a	0.1

Means in each column with different lowercase letters are significantly different at $P < 0.05$.

3.2. Regional Differences in Resource Consumption and Environmental Effects of Watermelon Production

Significant regional differences were also found in resource utilization burdens. The potentials for WD and ED per hectare in NC were higher than in the other regions. From the perspective of yield, however, the lowest burdens were observed in SW (Figure 4). The REI values of NC, NW, and SW were 0.10, 0.12, and 0.17, respectively (Figure 3). Across all regions, the mean total GHG, AP, and EP of watermelon production were 120 kg CO₂-eq (range: 87-150 kg CO₂-eq), 2.77 kg SO₂-eq (range: 1.97-3.32 kg SO₂-eq), and 0.907 kg PO₄-eq (range: 0.64-0.99 kg PO₄-eq), respectively (Table S5). The mean ranges of agricultural LO, WD, and ED were respectively 200-571 m², 11-16.5 m³, and 549-885 MJ (Table S5).

Significant differences in GHG, AP, and EP were also identified among regions. On a yield basis, the highest impacts were recorded in SW, at 151 kg CO₂-eq t⁻¹, 3.32 SO₂-eq t⁻¹, and 1.09 kg PO₄-eq t⁻¹, respectively. Interestingly, in SW, GHG emissions during the MS were higher than those during the FS, which contrasted with the patterns observed in NC and NW (Table 2). On an area basis, NC recorded the highest GHG, AP, and EP levels, at 6109 kg CO₂-eq ha⁻¹, 153 SO₂-eq ha⁻¹, and 50.2 kg PO₄-eq ha⁻¹, respectively. Again, in SW, GHG emissions during the MS exceeded those during the FS (Table 2). In addition, REI in NC was significantly lower than in the other two regions (Figure 3).

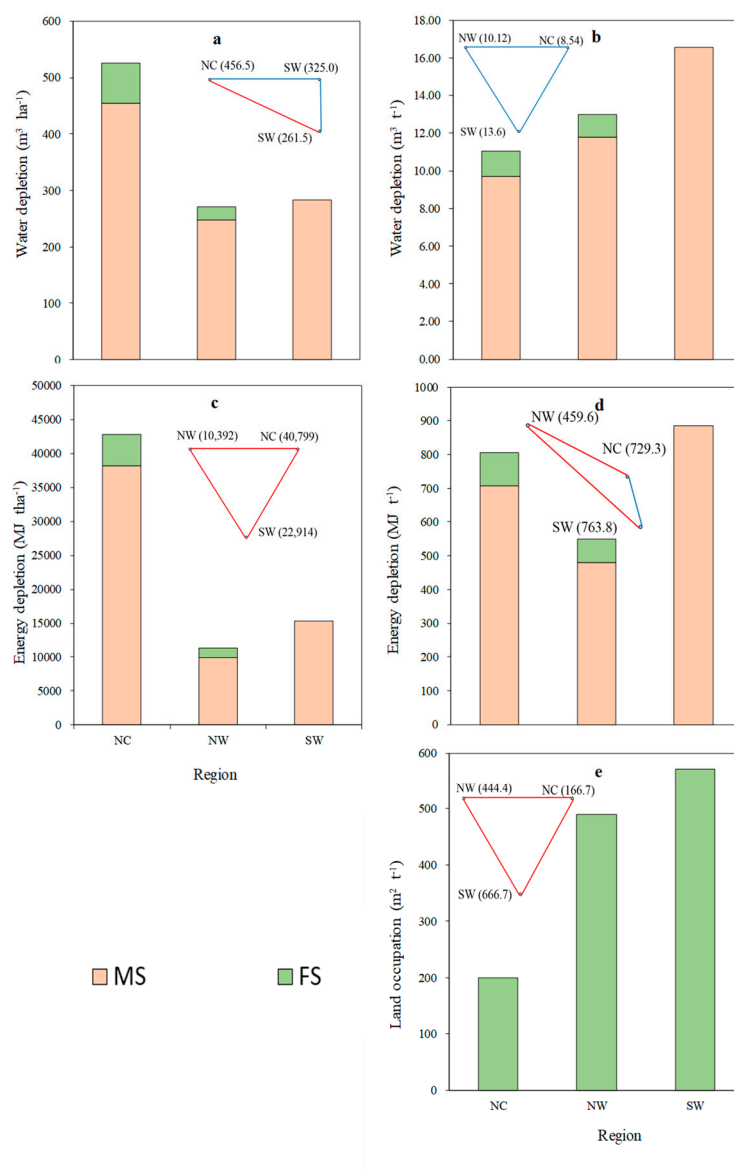


Figure 4. Resource burden of watermelon in 3 regions. The potential of (a, b) water resource depletion (WD), (c, d) energy depletion (ED) and (e) land occupation (LO) in per unit. Non-parametric tests were examined for each image, where red represents a significant difference ($p < 0.05$) and blue on the contrary.

3.3. Analysis of Key Influencing Factors of Resource Consumption and Environmental Effects

Analysis of REI showed that LO contributed the most overall, followed by EP. However, in NC, EP exceeded LO in its contribution (Figure 5). Moreover, the comprehensive index was the highest in SW (Figure 5). Nutrient input was identified as the main factor driving GHG, AP, and EP. For GHG, chemical fertilizers were the dominant contributor, accounting for approximately 47.2%-76.4%, while organic fertilizers contributed 17.1%-42.0%. For AP, fertilizers accounted for 31.4%-67.3%, with chemical fertilizers being the predominant source in NC. For EP, chemical fertilizers contributed 31.1%-66.5%, while organic fertilizers played a greater role in SW (Figure 6a). When comparing stages, nutrient inputs during FS had greater impacts on environmental emissions than those during MS. Specifically, nutrient inputs in FS contributed 47.1%-69.7% of GHG, 93.4%-96.9% of AP, and 97.7%-98.9% of EP (Figure 6b).

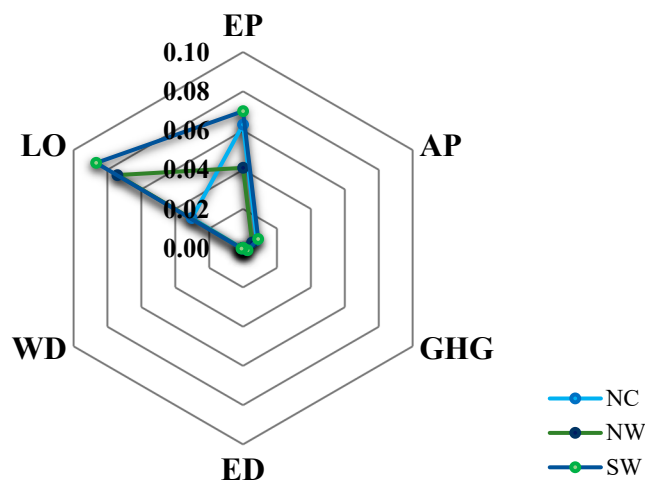


Figure 5. The weighted resource and environmental impact index of NC, NW and SW.

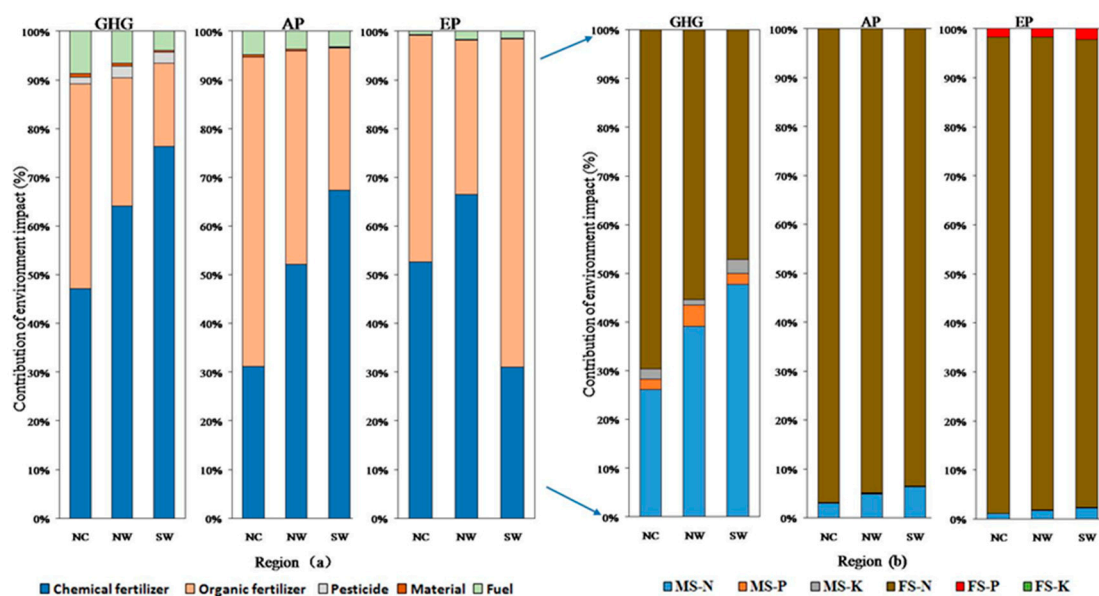


Figure 6. (a) Contribution of individual inputs to the total GHG emissions, acidification potential and eutrophication potential. (b) Contribution of individual fertilizer inputs.

3.4. Optimization Potential of Fertilization for Energy Conservation and Emission Reduction

Compared with FP, OPT did not significantly change yields, although a slight upward trend was observed. $PPFN_N$, however, improved markedly, by 43.3%-148%. Apart from LO, OPT significantly reduced other forms of resource consumption and environmental emissions. REI was reduced by 14.3%-40.0% in NC and by 16.7%-30.8% in SW (Table 3).

4. Discussion

4.1. Resource Consumption Showed Significant Regional Characteristics

Watermelon production in NC resulted in substantial WD and ED (Figure 4a, c). However, LCA analysis showed that when expressed per unit yield, WD, ED, and LO were highest in SW (Figures 4b, 4d, 4e). This is because watermelon production in NC involved a large amount of agricultural inputs, leading to significantly higher yields compared with NW and SW (Table 1). Although SW has the lowest investment in agricultural inputs, it is primarily located in mountainous areas, whereas

NC is mainly plains [33]. Consequently, the soil and environmental conditions in SW are relatively poorer, and its watermelon yield is significantly lower than that in other regions [34]. In addition, irrigation in SW relies mainly on rainfall, which may also contribute to the lower yield [35]. ED accounted for more than 80% of total energy use due to extensive energy extraction, consistent with findings for Chinese cereal crops [36,37].

Input and output play an irreplaceable role in determining LCA results [21]. As a fresh-market crop, watermelon yield serves as a hub linking the two functional units. When expressed per hectare of planted area, NC had the highest total nutrient inputs, pesticide application, agricultural plastic film use, and water, electricity, and diesel consumption among the three regions, with values 0.33-5.61 times higher than those in other regions (Table 1). For example, agricultural plastic film in NC involves multiple production modes, including single-film, double-film, and multi-layer systems (Table S1). As a result, plastic film use in NC was 5.02 and 6.04 times higher than in NW and SW, respectively.

The utilization of agricultural resources depends on local production practices, while environmental conditions influence the choice of production mode [38]. Geographical climate and farmers' practices drive regional differences in resource consumption. During the growth period, the abundant rainfall in SW reduced water consumption during the FS (Table S1). By contrast, fertilizer and pesticide production in NC consumed large amounts of water in the MS [31,39,40], resulting in significantly higher total consumption than in NW. Therefore, when considering the environmental factors that affect watermelon growth, yield is a critical factor, as it directly relates to resource input and consumption [41,42].

4.2. Environmental Effects Showed Significant Regional Characteristics

Compared with other crop systems, resource consumption in Chinese watermelon production is relatively low. However, the environmental footprint is comparatively high. In particular, environmental emissions in China, especially in SW and NC (Table S5, Figure S1), exceed those in other countries. This is due to the prominent role of Chinese watermelon production in the global market [9], which requires high production capacity and substantial inputs, resulting in significant environmental pollution [32,43].

Similar to resource consumption, the environmental effects of watermelon production were found to vary significantly across regions. On a per-hectare basis, NC showed the highest GHG, AP, and EP, while on a per-yield basis, SW had the highest values (Table 2). This reflects both the relatively high input of agricultural materials in these regions compared with NW (Table 1) and differences in growing conditions and management practices, which contribute to yield gaps and influence environmental effects [6,42].

Excessive fertilizer application, particularly N fertilizer, is a major factor driving high environmental emissions (Figure 6). Compared with P and K fertilizers, the production and transport of N fertilizers generate substantial GHG emissions. During the FS, N fertilizers also dominate environmental impacts (Figure 6). Although P and K fertilizer use in SW is relatively high, N fertilizer remains the primary contributor to GHG, AP, and EP (Table 1). These patterns are consistent with findings from other crop systems [4,6,44]. In addition to affecting emissions, N fertilizer also influences yield during watermelon growth [45]. Across NC, NW, and SW, the proportion of HH farms remains relatively low, and average REI can be reduced by 46.5%, 55.4%, and 48.3%, respectively (Figure 3). Under optimal conditions, environmental emissions can be minimized while achieving high yields [46]. Therefore, optimizing planting management and reducing inputs of agricultural chemicals, especially N fertilizers, is crucial for mitigating environmental impacts [18].

4.3. The Potential for Resource Use Reduction in Watermelon Production

Watermelon nutrient studies indicate that only 1.25-3.10 kg of N is absorbed in 1 t of fruit [47,48]. For example, in NC, expert recommendations suggest N fertilizer application of 5.22-7.91 kg t⁻¹

[49,50]. However, the actual farmer application observed in this survey was 9.83 kg t⁻¹, indicating more than 20% room for adjustment (Table 3).

Optimizing fertilizer use, particularly N fertilizer (Table 3), not only significantly improves PFP_N but also mitigates LO, WD, ED, GHG, AP, and EP, resulting in substantial reductions in REI ($p < 0.05$). This confirms that excessive fertilizer use occurs in current watermelon production across regions. Simple optimization of fertilizer application can reduce resource consumption and environmental impacts while maintaining yield [21].

Moreover, adopting fertilization management techniques such as the "4R" principles can further enhance the utilization efficiency of N fertilizer, enabling additional reductions in fertilizer input and environmental emissions [51,52]. Therefore, implementing reasonable measures to reduce input while improving efficiency, along with adjustments to watermelon planting practices, is key to achieving green and sustainable development in China's watermelon production system.

5. Conclusions

This study systematically evaluated the regional characteristics of resource consumption and environmental impacts in China's watermelon production system and analyzed the key factors influencing these impacts across different regions. Moreover, optimization fertilization experiments conducted in different regions verified the potential of reducing resource use in watermelon production. Significant regional differences were observed in the Chinese watermelon production system. In NC, watermelon yield was approximately 2.84 times that in SW, resulting in significant differences in resource consumption and environmental impacts per unit area. On a per-hectare basis, NC exhibited the highest resource consumption and environmental effects, whereas on a per-yield basis, SW showed the greatest impacts. Furthermore, N fertilizer was identified as the most critical factor driving environmental emissions. Reducing N fertilizer application by 20% can significantly decrease resource consumption and environmental impacts while maintaining watermelon yield. Furthermore, adopting optimized fertilization methods can further increase yield, reduce resource consumption, improve environmental outcomes, and promote sustainable, green development in watermelon production.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

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