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Article

A Life Cycle-Based Integrated Assessment of Environmental Burdens and Economic Benefits of Soybean Cultivation across Multiple Provinces

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Abstract: To reveal regional differences in the environmental and economic performance of soybean cultivation, this study evaluated production systems in Heilongjiang, Hubei, Shandong, and Sichuan using life cycle assessment and life cycle cost analysis. A system boundary covering cultivation and processing stages was established to quantify environmental impacts, environmental external costs, and economic returns. The results revealed significant regional differences. Shandong exhibited the highest normalized environmental impact, followed by Hubei, Heilongjiang, and Sichuan. By-product processing, refining, and main-product processing were the major contributors to environmental impacts, with by-product processing accounting for approximately 50% of the total impact. Environmental risk contribution analysis showed that air- and soil-related impacts dominated the environmental external cost structure, together accounting for more than 94% of the total environmental external cost across all four provinces. From the producer perspective, Hubei and Shandong achieved the highest net incomes, whereas Heilongjiang experienced a net loss. After environmental external costs were incorporated, the environment-adjusted net incomes of all four provinces became negative, indicating that current market returns were insufficient to offset life cycle environmental damage costs. These findings suggest that improving the environmental-economic sustainability of soybean cultivation should prioritize cleaner processing, optimized agricultural input management, higher production efficiency, and region-specific policy measures to reduce environmental externalities.

Keywords: soybean cultivation; life cycle assessment; life cycle cost analysis; environmental external cost; environmental risk contribution

1. Introduction

Soybean is an important crop in China with both grain and oil uses [1]. It is a major source of edible vegetable oil and an important protein feedstock for animal husbandry [2]. It also plays a key role in food security, crop-structure adjustment, and the resilience of agricultural product supply [2,3]. With the upgrading of dietary consumption and the expansion of livestock production, the demand for soybean and soybean-based products has remained high [4]. However, soybean production in China is widely distributed across regions. Different provinces vary greatly in natural resource conditions, cropping systems, mechanization levels, agricultural input structures, yield per unit area, and market returns [5,6]. These differences affect not only the economic returns of soybean cultivation, but also resource consumption, pollutant emissions, and environmental external costs throughout the life cycle [7]. Therefore, evaluating soybean cultivation only from the perspective of economic return is no longer sufficient to reflect its real sustainability. Environmental impacts and economic returns need to be included in a unified assessment framework.

Traditional agricultural economic evaluation usually focuses on production cost, output value, net income, and cost-profit ratio [8]. These indicators can reflect the direct economic returns received by farmers or producers under market conditions. For example, when a province has a high soybean output value and low internal production cost, its producer net income and cost-profit ratio are usually higher. This means that soybean cultivation in that region has better practical economic feasibility [8]. However, agricultural production does not only generate market returns. It also causes environmental burdens, such as fertilizer production and application, fuel consumption from machinery, nitrogen and phosphorus losses through runoff, leaching, and gaseous emissions from agricultural fields, irrigation water use, energy use in processing, and waste emissions [7]. These environmental impacts are often not fully included in agricultural product prices. They therefore appear as typical environmental externalities. If these external costs are ignored, judging whether soybean cultivation is “economic” only by producer income may overestimate its overall performance [9,10].

Life cycle assessment can trace resource inputs, energy use, and pollutant emissions within the full life cycle of a product or agricultural system based on a defined system boundary [11,12]. It is suitable for evaluating the multiple environmental impacts of crop production and processing. Life cycle cost analysis further combines internal production costs with environmental external costs [13,14]. It uses monetary values to measure the contribution of different stages and environmental impact categories to the total social cost. By combining life cycle assessment with life cycle cost analysis, two questions can be addressed. First, how large are the environmental impacts of soybean cultivation and processing in different provinces, and which stages contribute the most? Second, after environmental external costs are considered, does the economic evaluation of soybean cultivation change?

Based on this logic, this study selects Heilongjiang, Hubei, Shandong, and Sichuan as the research areas. A cradle-to-processing life cycle system boundary was established for soybean cultivation, covering agricultural operations (tillage, sowing, field management, and harvesting) and subsequent processing stages, including main-product processing, by-product utilization, and refining. Within this framework, life cycle assessment (LCA) was conducted to quantify the comprehensive environmental impacts of soybean cultivation and processing across the four provinces. The environmental impact results were further integrated with economic indicators through life cycle cost analysis (LCC), enabling the calculation of internal production costs, environmental external costs, total social costs, and environment-adjusted net income.

The main objective of this study was to develop an integrated environmental-economic assessment framework for soybean cultivation and processing in four representative provinces of China, with the aim of identifying the trade-offs between environmental impacts and economic benefits and proposing region-specific optimization strategies for sustainable soybean production. To achieve this objective, this study focused on four aspects: (1) establishing a life cycle assessment system boundary to characterize the input-output relationships of soybean cultivation and processing; (2) evaluating life cycle environmental impacts and identifying the major contributors to environmental burdens and external costs; (3) assessing regional economic performance by comparing production costs, output values, net incomes, and benefit-cost ratios; and (4) incorporating environmental external costs into economic evaluation to estimate total social costs and environment-adjusted net incomes. Based on the integrated environmental and economic assessment, differentiated strategies were proposed to improve the sustainability of soybean production in different regions.

2. Materials and Methods

2.1. System Boundary and Life Cycle Stages

The life cycle system boundary of soybean production established in this study is illustrated in **Figure 1**. The assessment covers the entire production chain from field cultivation to soybean processing and utilization, including both upstream agricultural activities and downstream processing operations. The cultivation stage comprises tillage, sowing, field management, and harvesting, where inputs such as machinery operation, fuel consumption, seeds, fertilizers, pesticides, irrigation, and field emissions are considered. Following crop production, the processing stage includes main-product processing, by-product utilization, and refining, accounting for the energy and material requirements associated with soybean processing.

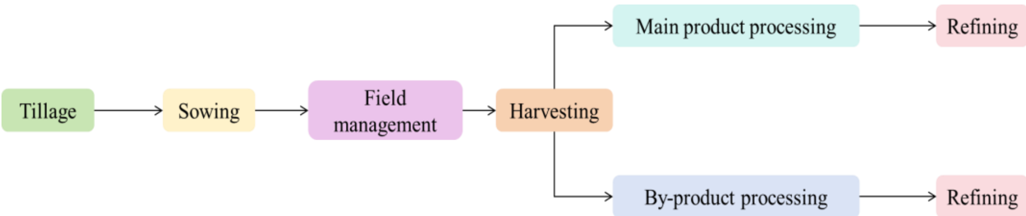

Figure 1. Life cycle system boundary of soybean cultivation and processing.

By integrating both cultivation and processing stages, the established system boundary provides a comprehensive representation of the environmental impacts associated with soybean production. Compared with assessments limited to field-level cultivation, this expanded boundary enables a more complete identification of environmental burden sources throughout the soybean life cycle, particularly the contributions of processing energy consumption and by-product utilization to overall environmental performance.

2.2. Life Cycle Assessment Method

This study used the open-source software Activity Browser (version 2.11.2; Institute of Environmental Sciences, Leiden University, Leiden, the Netherlands)and the ReCiPe 2016 v1.03 midpoint impact assessment method (National Institute for Public Health and the Environment [RIVM], Bilthoven, the Netherlands)to evaluate the environmental impacts of soybean production systems in the four provinces [15,16]. Heilongjiang is a traditional major soybean-producing province in China, with a strong production base and a relatively high level of mechanization [17]. Shandong is located in the Huang-Huai-Hai region, where agricultural production conditions are favorable and output value per unit area is relatively high [18]. Hubei represents soybean production in the middle reaches of the Yangtze River [19]. Sichuan is characterized by complex terrain in Southwest China, higher labor input, and relatively weaker income per unit area [20]. The selection of these four provinces helps compare regional differences in soybean environmental burdens and economic returns. It also helps identify the key factors affecting environmental-economic coordination.

The life cycle inventory data—including the application rates of fertilizers, pesticides, seeds, agricultural films, irrigation water, diesel, and other inputs, as well as the yields of main products and by-products—were obtained from the 2005–2024 editions of the National Agricultural Product Cost-Benefit Data Compilation [21]. Upstream emission factors associated with the production of agricultural inputs, farm machinery operations, and energy consumption during processing were obtained from the ecoinvent v3.8 database (ecoinvent Association, Zurich, Switzerland).The direct soil N_2O emission factor were estimated using the Tier 1 method in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, issued by the Intergovernmental Panel on Climate Change (IPCC, Geneva, Switzerland), with an emission factor of 0.01 kg N_2O-N per kg N applied [22]. The emission factors for indirect N_2O emissions from atmospheric deposition and nitrogen leaching/runoff were set at 0.01 and 0.0075 kg N_2O-N per kg N, respectively. The NH_3 volatilization coefficient was also adopted from the 2019 IPCC Refinement guidelines and was set at 10% of the nitrogen input from chemical fertilizers [22]. For the life cycle cost analysis, the monetary conversion factors were based on the endpoint damage factors of ReCiPe 2016 [15], and values expressed in euros were converted into Chinese yuan at an exchange rate of EUR 1 = CNY 8.0. The LCA results of different environmental impact categories were further normalized using the normalization factors provided by ReCiPe 2016 [15]. Specifically, the characterized impact results were divided by the corresponding reference values to obtain dimensionless normalized scores, enabling comparison of environmental burdens among different provinces, life cycle stages, and impact categories.

The comprehensive environmental impact was calculated as follows:

$$EI_i = \sum_{j=1}^{n} I_{ij} \times NF_j \tag{1}$$

where (EI_i) is the comprehensive environmental impact of province (*i*); (I_{ij}) is the characterization result of province (*i*) for environmental impact category (*j*); and (NF_j) is the normalization factor of environmental impact category (*j*).

2.3. Life Cycle Cost Analysis Method

The economic accounting in this study includes two aspects: producer economic return and environment-adjusted return. Producer economic return considers only internal production costs and total output values from the producer perspective. Data on agricultural inputs, production costs, soybean yield, product prices, and output values were obtained from the National Agricultural Product Cost-Benefit Data

Compilation (2005–2024 editions) [21]. The producer net income was calculated as follows:

$$NI_i = TV_i - IC_i \tag{2}$$

where (NI_i) is the producer net income of province (i), (TV_i) is the total output value, and (IC_i) is the internal production cost.

Furthermore, the environmental impacts were monetized as environmental external costs, and the total social cost was constructed as follows:

$$STC_i = IC_i + EC_i \tag{3}$$

$$SNI_i = TV_i - STC_i = TV_i - IC_i - EC_i \tag{4}$$

where (STC_i) is the total social cost, (EC_i) is the environmental external cost, and (SNI_i) is the environment-adjusted net income. This indicator does not represent the actual income of farmers. Instead, it measures whether the benefits from soybean cultivation can cover production costs and environmental damage costs from the perspective of society as a whole.

To further identify the dominant environmental compartments contributing to the environmental external cost, a contribution analysis approach was applied. Contribution analysis is a widely used approach in life cycle assessment for identifying the relative importance of individual processes or impact categories within the overall environmental burden [23]. Based on this principle, the environmental risk contribution (ERC) was defined as the proportion of the monetized environmental external cost associated with each environmental compartment relative to the total environmental external cost. The ERC was calculated as follows:

$$ERC_i = \frac{EC_i}{\sum_{i=1}^{n} EC_i} \times 100\% \tag{5}$$

where ERC_i represents the environmental risk contribution of compartment i, and EC_i denotes the monetized environmental external cost of the corresponding compartment.

2.4. Statistical analysis

The retrieved inventory data and calculated indicators were processed and analyzed using Microsoft Excel 2021. Descriptive statistics were applied to summarize the input data, production costs, environmental impacts, and economic indicators of soybean production in the four provinces. The calculated results were compared among provinces to identify regional differences in environmental performance and economic benefits. In addition, contribution analysis was conducted to determine the relative importance of different environmental compartments to the total environmental external cost. All calculations were performed based on the same functional unit and system boundary to ensure comparability among regions.

3. Results and Analysis

3.1. Differences in Life Cycle Environmental Impacts among the Four Provinces

Clear differences in the normalized environmental impact index were observed among the four soybean-producing provinces. The comprehensive environmental impact index followed the order of Shandong, Hubei, Heilongjiang, and Sichuan from high to low (**Figure 2**). Shandong showed the highest index value of 1302, indicating a relatively higher environmental burden under the defined life cycle system boundary. Sichuan showed the lowest index value of 821, representing a relatively lower environmental burden among the four provinces. Since normalization converts characterized environmental impacts into dimensionless values, the index reflects relative environmental burden rather than absolute environmental emissions. Therefore, the values are mainly used for comparison among regions and life cycle stages. From the perspective of life cycle stage contribution, the environmental impacts in all four provinces were mainly concentrated in by-product processing, refining, and main-product processing. In contrast, tillage, sowing, field management, and harvesting made smaller contributions. By-product processing was the largest source of environmental impact in the soybean life cycle, contributing about 50% in each province. This high contribution means that the treatment of by-products, such as soybean straw and soybean hulls, has a strong effect on the overall environmental results. On the one hand, by-product processing usually requires electricity, fuel, or other forms of energy. On the other hand, different by-product utilization pathways may change the distribution of environmental impacts and the burdens within the system boundary. Therefore, in the improvement of sustainable soybean production and processing, by-product treatment should not be regarded as a marginal process. Instead, it should be treated as an important entry point for reducing environmental burdens.

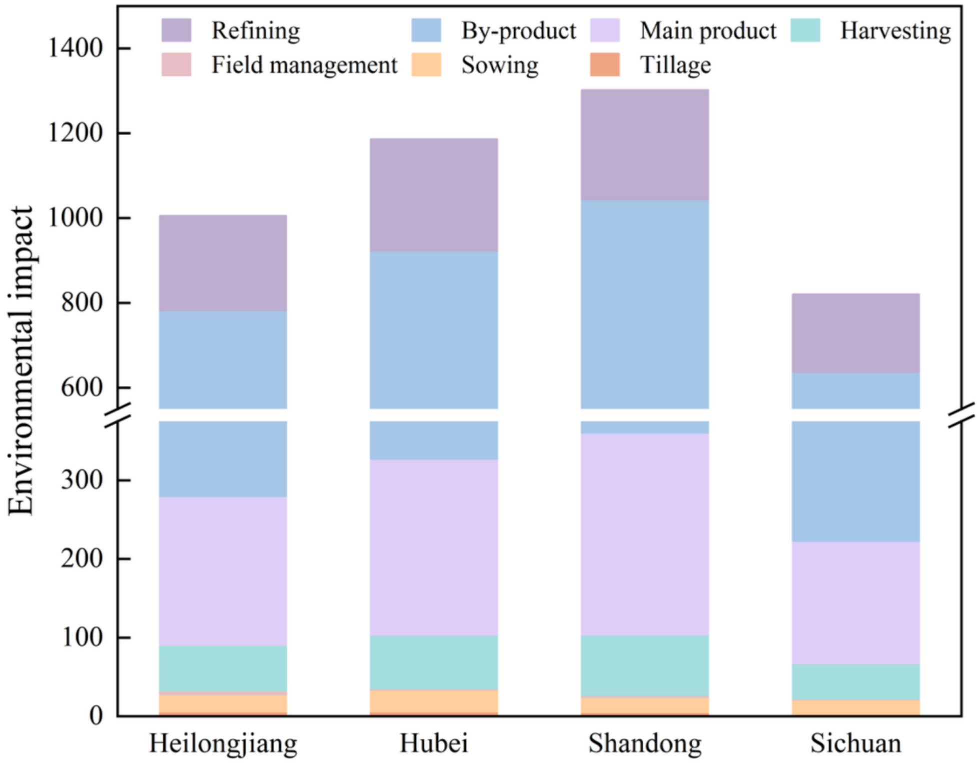

Figure 2. Contribution of different life cycle stages to the environmental impacts.

Refining and main-product processing were also important sources of environmental impact, accounting for about 22% and 19%, respectively. The contribution of main-product processing in Shandong was clearly higher than that in the other provinces. This was related to its higher soybean yield per unit area and larger processing scale. Hubei and Shandong had relatively high environmental impacts in the processing stages. This means that although they performed well in terms of economic returns, energy use and environmental pressure in the processing process were also more pronounced.

By comparison, the contribution of field management was relatively low, with an average share of only about 0.25% across the four provinces. Tillage, sowing, and field management involve diesel, seeds, fertilizers, pesticides, and irrigation inputs. However, within the full life cycle system boundary used in this study, their contributions were lower than those of the processing stages. This does not mean that field inputs can be ignored. Rather, it means that when processing stages are included, the environmental impacts of processing are greatly amplified. In particular, when the functional unit is defined as 1 hm^2 of soybean production and subsequent processing, a higher yield per unit area means that more soybean grains enter the processing system. If processing inputs are scaled according to output, energy and material consumption in the processing stages will also increase, leading to higher comprehensive environmental impacts.

The differences among the four provinces were also related to yield per unit area. In 2023, soybean yield in Shandong was 3031 kg/hm^2, which was higher than that in Hubei, Heilongjiang, and Sichuan, at 2642, 2232 and 1838 kg/hm^2, respectively. A higher yield means that more soybean grains enter the processing system. When the processing process is scaled according to yield, environmental impacts from the processing stages increase accordingly. This is an important reason why Shandong had the highest comprehensive environmental impact. Sichuan had a lower yield and a smaller processing scale, so its comprehensive environmental impact was also lower. From an economic perspective, however, a lower yield may also lead to insufficient total output value and affect producer income.

Although a unified optimal environmental benchmark for soybean production in China has not yet been established, Sichuan, which exhibited the lowest normalized environmental impact index in this study, can be considered a relative reference among the four provinces. Compared with this reference level, the higher index values observed in Shandong, Hubei, and Heilongjiang indicate greater opportunities for improving processing efficiency and reducing environmental burdens.

Overall, the results indicate that the environmental burden of soybean production showed both stage concentration and regional differences. Stage concentration is reflected in the dominant contributions of by-product processing, refining, and main-product processing. Regional differences are reflected in the higher environmental impacts in Shandong and Hubei, the intermediate level in Heilongjiang, and the lowest level in Sichuan. These results suggest that future environmental impact control for soybean production in the four provinces should go beyond the traditional focus on field inputs. More attention should be given to energy saving in processing, improvement of processing efficiency, high-value utilization of by-products, and optimization of the energy structure.

3.2. Contribution Characteristics of Different Environmental Impact Categories

The normalized environmental impacts of soybean production were mainly dominated by freshwater ecotoxicity potential (FETP) across the four provinces. As shown in **Figure 3**, the evaluated impact categories included freshwater ecotoxicity potential (FETP), terrestrial ecotoxicity potential (TETP), global warming potential (GWP), land occupation potential (LOP), freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), human toxicity potential (HTPc), and other impact categories with relatively minor contributions (grouped as “Others”). Among these categories, FETP had the largest share in the comprehensive environmental impact of all four provinces, accounting for 85.3%–88.6% of the total normalized environmental impact. The contribution of FETP was substantially higher than that of the other impact categories, with the second-largest category (TETP) accounting for only 4.1%–4.6%. The differences in total environmental impacts among Heilongjiang, Hubei, Shandong, and Sichuan were therefore largely determined by variations in FETP contributions. Shandong showed the highest FETP contribution (1153.38), whereas Sichuan exhibited the lowest FETP contribution (708.62), corresponding to their highest and lowest overall normalized environmental impact indices, respectively. Within the four provinces evaluated in this study, Sichuan showed the lowest normalized environmental impact index and was considered a relative reference level for comparison. Compared with Sichuan, the normalized environmental impact indices of Heilongjiang, Hubei, and Shandong were 1.22, 1.45, and 1.59 times higher, respectively. This comparison provides a clearer interpretation of the relative environmental performance differences among the studied soybean production systems. The high contribution of FETP may be related to pesticide and fertilizer use, energy production, emissions from processing, and pollutant releases from related background processes. During soybean cultivation, pesticide and fertilizer inputs may affect aquatic ecosystems through runoff and leaching. At the same time, electricity, steam, diesel, and chemicals consumed in the processing stages may also lead to upstream emissions of heavy metals, organic pollutants, or other substances related to ecotoxicity. Therefore, the large share of FETP in the normalized results means that environmental optimization of the soybean life cycle should not focus only on greenhouse gas emissions. More attention should also be paid to the potential effects of agricultural inputs, processing energy, and pollutant emissions on freshwater ecosystems.

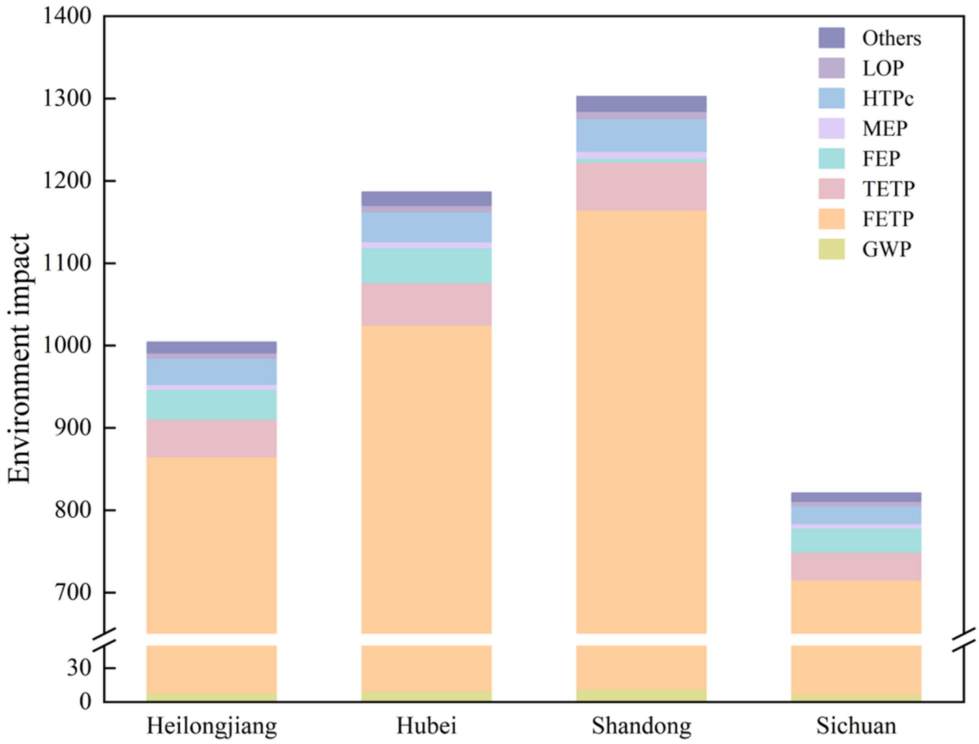

Figure 3. Contribution of different environmental impact categories to soybean life cycle impacts.

In addition to FETP, TETP, HTPc, FEP, and Others also contributed to the comprehensive environmental impact, but their individual contributions were much lower. For example, TETP accounted for only 4.1%–4.6%, while HTPc contributed approximately 2.7%–3.1% across the four provinces. Although their contributions were relatively small, TETP, HTPc, FEP, and other categories reflected additional environmental pressures associated with soybean production, including ecological toxicity, human health impacts, and freshwater eutrophication. These impacts were likely related to fertilizer and pesticide inputs during cultivation, as well as energy and chemical consumption in processing stages. The results indicate that environmental optimization should consider multiple impact pathways rather than focusing only on the dominant categories.

Overall, the results indicate that the life cycle environmental impacts of soybean production in the four provinces were strongly dominated by FETP. Although other categories, including TETP, HTPc, FEP, and GWP, contributed to the total impact, their contributions were relatively limited compared with FETP. The higher freshwater ecotoxicity-related impacts in Shandong and Hubei were important reasons why their comprehensive environmental impacts were higher than those of Heilongjiang and Sichuan. To reduce the life cycle environmental impacts of soybean production, future measures should focus on the ecotoxicity effects caused by pesticides, fertilizers, processing energy, and chemical inputs. At the same time, eutrophication, human toxicity, and greenhouse gas emissions should also be considered. For Shandong and Hubei, priority should be given to controlling freshwater ecotoxicity-related emissions and improving processing processes. For Heilongjiang, ecological impacts from agricultural inputs and energy use should be reduced while production costs are lowered. For Sichuan, improvements in yield and economic returns should be pursued while maintaining its relatively lower environmental impact level among the four provinces.

3.3. Environmental risk contribution analysis

The environmental external cost structure showed highly similar contribution patterns among Heilongjiang, Hubei, Shandong, and Sichuan. Air-related and soil-related impacts were the dominant contributors to the total environmental external cost in all four provinces (**Figure 4**). Despite regional differences in total environmental impacts, the relative contribution of different environmental compartments remained relatively stable.

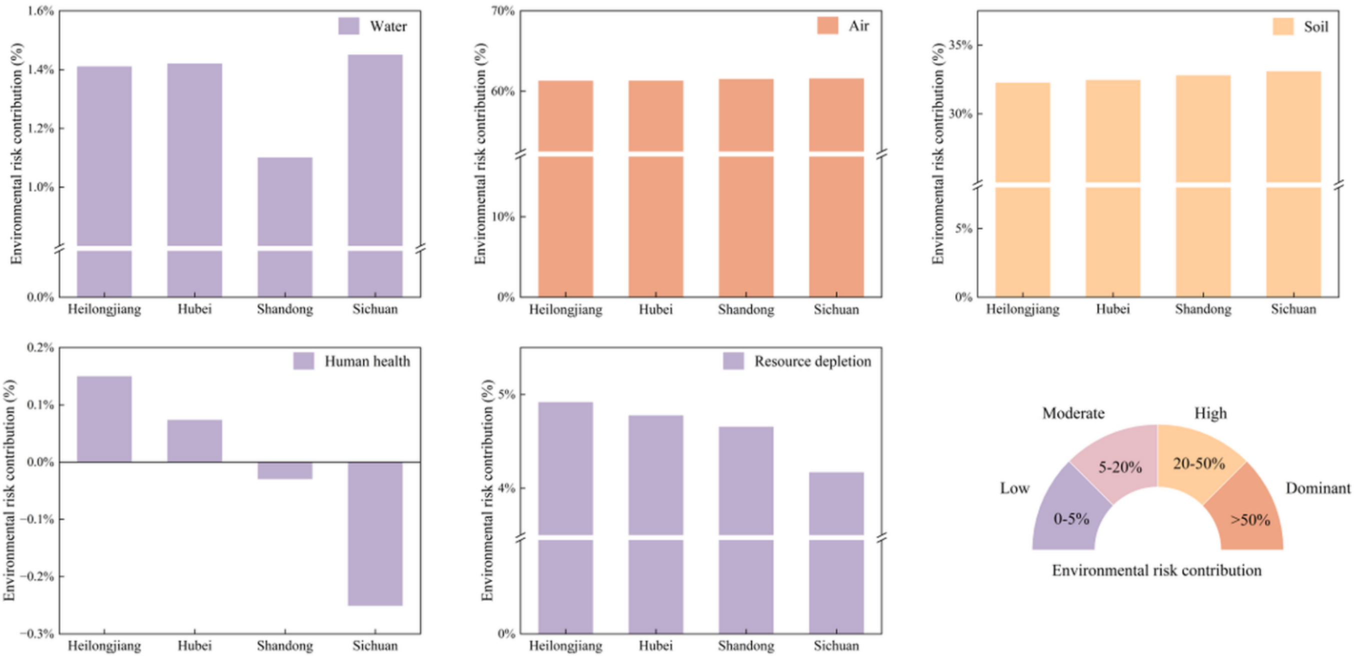

Figure 4. Environmental risk contribution of different environmental compartments in soybean cultivation across four provinces.

Among all environmental compartments, air-related impacts contributed the largest proportion of the total environmental external cost, accounting for approximately 61.3%–61.6% in all four provinces. This result indicates that atmospheric emissions generated during agricultural input production, energy consumption, and soybean processing were the dominant contributors to the overall environmental burden. Soil-related impacts ranked second, contributing 32.2%–33.0%, suggesting that soil ecotoxicity, land occupation, and related emissions also played an important role in determining the environmental performance of soybean production systems.

In comparison, the contributions of resource depletion and water-related impacts were much smaller, accounting for 4.2%–4.9% and 1.1%–1.5%, respectively. Resource depletion mainly originated from the consumption of fossil energy and mineral resources throughout the life cycle, whereas water-related impacts remained relatively low under the current production systems. Human health-related impacts fluctuated around zero, with slightly negative values observed in Shandong and Sichuan, indicating that environmental credits generated during certain life-cycle stages partially offset the corresponding environmental burdens.

Although differences existed in the total environmental external costs among the four provinces, their environmental risk contribution patterns were generally consistent. These results suggest that air emissions and soil-related environmental impacts were the principal contributors to the environmental external cost of soybean cultivation, together accounting for more than 94% of the total environmental burden. Therefore, reducing atmospheric emissions and mitigating soil-related impacts are expected to provide the greatest potential for improving the environmental sustainability of soybean production.

3.4. Comparison of Producer Economic Performance

Significant differences in producer economic performance were observed among the four provinces. These differences were reflected in internal production costs, total output values, net incomes, and cost-profit ratios (**Figure 5**).

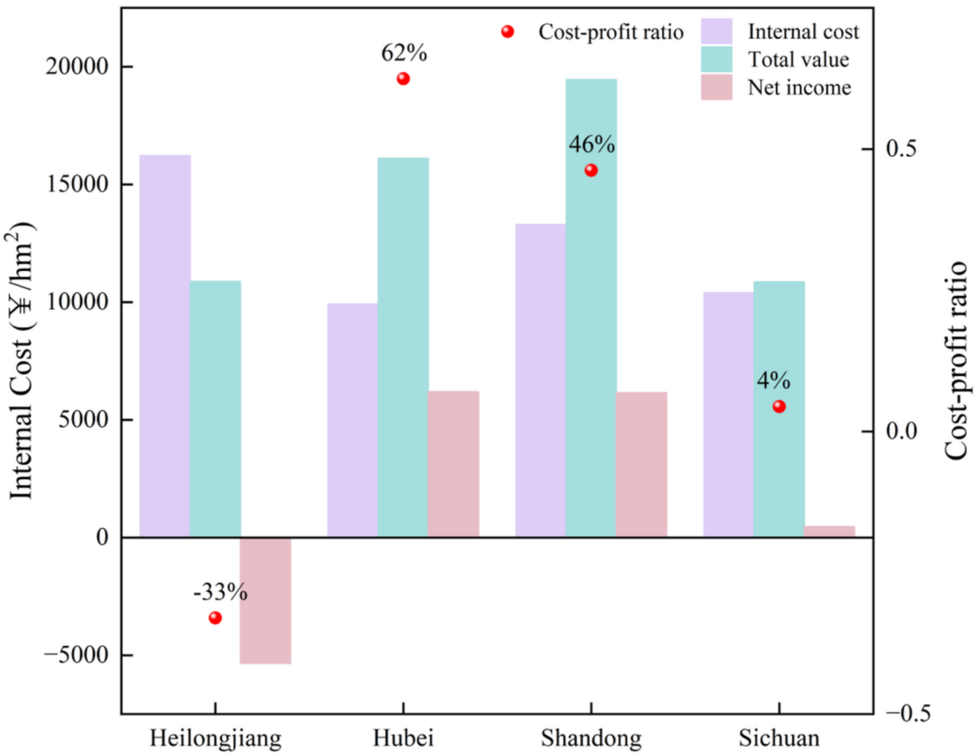

Figure 5. Comparison of producer economic performance of soybean cultivation.

In terms of internal cost, Heilongjiang had the highest value, reaching 16,223 yuan/hm^2, which was considerably higher than those of the other three provinces. The high production cost was mainly associated with land cost, machinery operation, and agricultural inputs. According to the data, land cost in Heilongjiang reached 647 yuan/mu, equivalent to 9698 yuan/hm^2 after conversion, representing a major component of total production cost.

Despite its status as a traditional soybean-producing province with a strong production foundation and relatively developed mechanization, Heilongjiang did not achieve a corresponding economic advantage under the current production and market conditions. The relatively high input costs were not fully compensated by output value, resulting in a negative producer net income. This suggests that a strong production base and high production capacity do not necessarily translate into higher profitability when cost increases exceed the growth of economic returns. Therefore, improving cost efficiency, increasing value-added returns, and optimizing production inputs are important for enhancing the economic sustainability of soybean cultivation in Heilongjiang.

Hubei had the lowest internal cost, at 9915 yuan/hm^2, while its total output value reached 16,107 yuan/hm^2. As a result, its producer net income was 6191 yuan/hm^2, and its cost-profit ratio reached 62.44%, the highest among the four provinces. This shows that soybean cultivation in Hubei had strong cost control and good input-output efficiency in 2023. Although the total output value of Hubei was lower than that of Shandong, its lower internal cost allowed it to achieve a slightly higher net income than Shandong. This result also suggests that, in agricultural economic evaluation, a higher total output value does not always lead to the highest net income. Cost control is also an important factor affecting profitability.

Shandong had the highest total output value, at 19,443 yuan/hm^2. Its producer net income was 6147 yuan/hm^2, and its cost-profit ratio was 46.23%. The yield of soybeans in Shandong was relatively high, with the main-product yield reaching 3031 kg/hm^2. This higher yield increased the total output value and enabled Shandong to maintain a relatively high net income, even though its internal cost was higher than that of Hubei. The economic advantage of Shandong was mainly reflected in its high output value. However, its cost-profit ratio was lower than that of Hubei, which means that its profitability depended more on high output than on a low-cost advantage. If Shandong can further reduce production costs while maintaining a high output value, its economic performance still has room for improvement.

The internal cost in Sichuan was 10,395 yuan/hm^2, and its total output value was 10,855 yuan/hm^2. Its producer net income was only 460 yuan/hm^2, with a cost-profit ratio of 4.42%. Although soybean cultivation in Sichuan did not suffer a loss, its profit margin was very limited. The soybean yield in Sichuan was 1838 kg/hm^2, the lowest among the four provinces, and its total output value was also relatively low. At the same time, labor cost in Sichuan was high, reaching 500 yuan/mu, equivalent to 7496 yuan/hm^2 after conversion. This placed considerable pressure on the total cost. Due to limited output value growth and high labor input, the producer economic performance of soybean cultivation in Sichuan was relatively weak.

Overall, the producer economic performance of the four provinces can be divided into three types. The first type includes Hubei and Shandong, both of which had relatively high positive net income. Hubei mainly relied on a low-cost advantage, while Shandong mainly relied on a high-output-value advantage. The second type is Sichuan, which had a small positive net income but weak profitability. The third type is Heilongjiang, where net income was negative. This means that, under the current cost and price conditions, soybean cultivation in Heilongjiang faces considerable economic pressure. These results show that the economic performance of soybean cultivation has clear regional differences. These results indicate that soybean profitability cannot be evaluated solely based on production scale or regional importance. Instead, profitability depends on the interaction among cost structure, yield level, input efficiency, and market returns.

3.5. Changes in Net Income in the Four Provinces from 2004 to 2023

The long-term trends in soybean cultivation net income showed clear differences among the four provinces from 2004 to 2023. Shandong maintained a relatively high level of net income over the study period, while Hubei experienced rapid income growth in recent years. Sichuan showed considerable fluctuations but achieved positive net income in recent years, whereas Heilongjiang gradually entered a negative-income range after 2013 with an expanding loss trend (**Figure 6**). The time-series analysis provides a dynamic perspective on changes in the economic performance of soybean cultivation and complements the limitations of single-year cross-sectional comparisons. The different trends among provinces reflect the influence of regional production conditions, cost changes, and market factors on soybean profitability over time.

Heilongjiang had the most unfavorable change in net income. From 2004 to 2012, its soybean net income was positive in most years, but the overall level was not high. After 2013, negative values began to appear frequently. After 2015, the degree of loss became more serious. In 2023, the net income of Heilongjiang fell to −5349 yuan/hm^2, the lowest among the four provinces. This trend shows that soybean cultivation in Heilongjiang has faced strong cost pressure in recent years. Possible reasons include rising land cost, higher machinery operation cost, increased prices of production materials, and insufficient growth in total output value. As a traditional major soybean-producing province, Heilongjiang has a large planting scale. However, its scale advantage has not been fully converted into an advantage in unit-area economic returns.

Shandong performed relatively steadily over the whole time series, and its net income remained higher than that of the other provinces for a long period. From 2004 to 2012, the net income of Shandong stayed at a relatively high level, exceeding 6000 yuan/hm^2 in some years. After 2015, its net income fluctuated. It once dropped to a lower level in 2019, but increased clearly after 2020. In 2023, it reached 6147 yuan/hm^2. The high net income in Shandong was mainly supported by its high yield per unit area and high total output value. Although its internal cost was also not low, its output-value advantage helped maintain good producer economic performance. The change in Shandong's net income shows that a high output value is an important basis for maintaining the profitability of soybean cultivation. However, net income may still fluctuate when costs and market prices change.

The data for Hubei were not continuous in some years. However, based on the available data, Hubei showed good net income performance. Especially after 2019, its net income increased gradually and reached 6191 yuan/hm^2 in 2023, slightly higher than that of Shandong. The advantage of Hubei did not come from the highest output value, but from its lower internal cost and higher cost-profit ratio. The improvement in its net income suggests that, under a certain yield level, better economic returns can also be achieved through cost control, input-structure optimization, and improved production efficiency. This trend in Hubei provides a useful reference for other provinces. It shows that improving the economic performance of soybean cultivation should not rely only on yield growth. Cost management is also important.

Sichuan had large fluctuations in net income. Its net income was negative in 2019 and 2020, turned positive in 2021, and reached a relatively high level in that year. It then declined, and in 2023 it was only 460 yuan/hm^2. This change shows that the economic performance of soybean production in Sichuan was relatively unstable. It was strongly affected by yield, labor cost, and market price. Due to complex terrain and relatively scattered production, Sichuan may have lower mechanization and scale levels than Northeast China and the Huang-Huai-Hai region. This leads to a higher share of labor cost and further reduces the space for net income. To improve the economic performance of soybean cultivation in Sichuan, future efforts should focus on increasing yield, improving mechanized service capacity, and controlling labor cost.

Figure 6 shows that the economic performance of soybean cultivation in the four provinces had both spatial differences and clear temporal changes. Shandong maintained a relatively high income level over a long period. Hubei performed well in recent years. Sichuan showed unstable returns. Heilongjiang faced increasing economic pressure. These results suggest that soybean production support policies should consider both income trends and cost-structure differences across provinces. For Heilongjiang, attention should be given to cost compensation and income stabilization mechanisms. For Shandong, high-yield and high-efficiency production should be coordinated with environmental emission reduction. For Hubei, the low-cost advantage should be maintained while green production is further improved. For Sichuan, yield and operating efficiency should be improved to strengthen income stability.

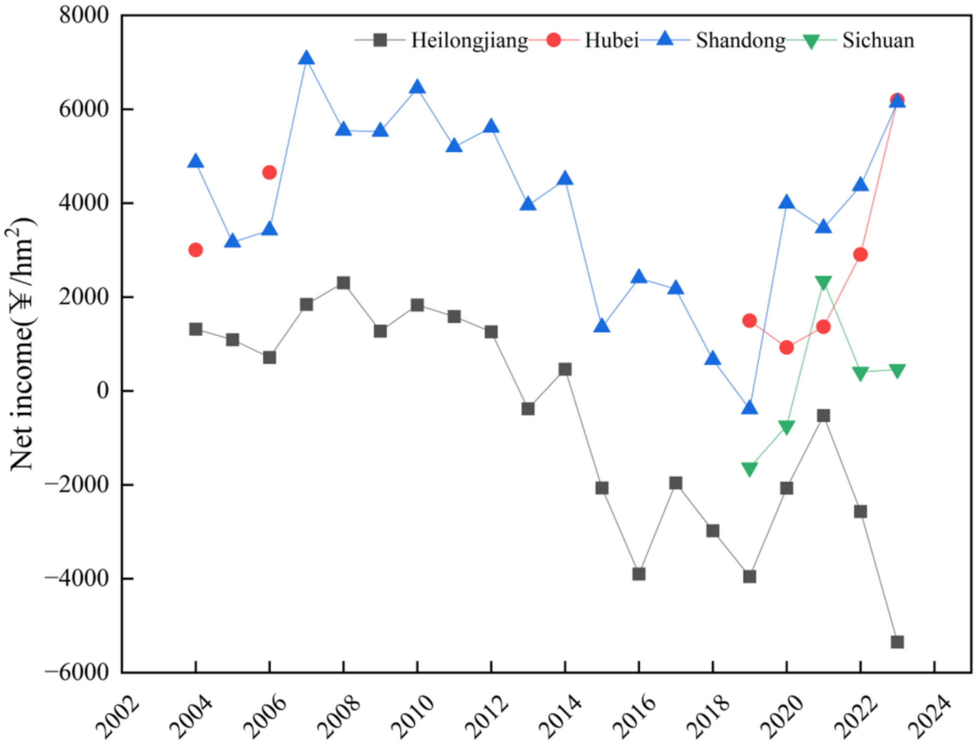

Figure 6. Changes in net income from soybean cultivation in four provinces from 2004 to 2023.

3.6. Analysis of Total Social Cost and Environment-Adjusted Net Income

To further evaluate the economic sustainability of soybean production, environmental external costs were incorporated into the traditional producer-oriented economic assessment. This analysis compared producer economic returns with total social costs, including both internal production costs and environmental damages, to examine how environmental externalities affect the overall economic performance of soybean cultivation. Incorporating environmental external costs substantially changed the evaluation of soybean production performance. The total social cost, consisting of internal production cost and environmental external cost, exceeded the total output value in all four provinces (**Figure 7**). Shandong had the highest total social cost at 148,746 yuan/hm^2, followed by Hubei (129,641 yuan/hm^2) and Heilongjiang (118,276 yuan/hm^2), whereas Sichuan showed the lowest value at 91,681 yuan/hm^2.

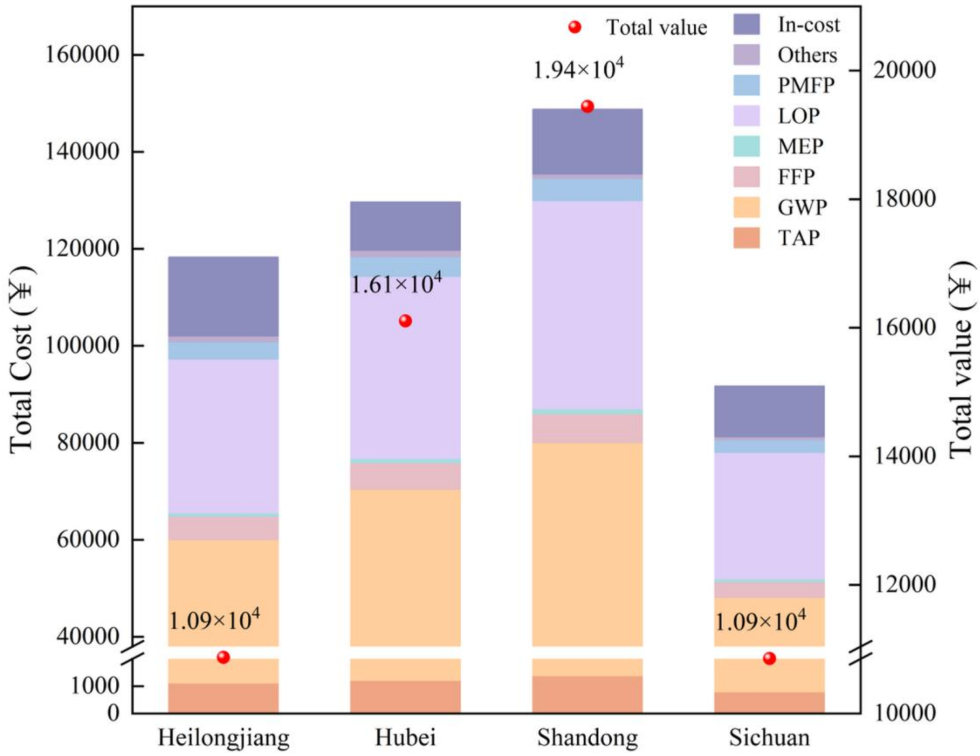

Figure 7. Composition of internal and external costs and comparison with total output value.

The differences in total social costs were mainly associated with variations in both production costs and environmental external costs among provinces. Shandong showed the highest environmental external cost, which was related to its higher GWP, LOP, and environmental impacts from processing stages. Hubei also showed a relatively high external cost, indicating that its high producer economic performance was accompanied by considerable life cycle environmental damage. Heilongjiang had lower environmental external costs than Shandong and Hubei; however, because its producer net income was already negative, the inclusion of environmental costs further increased its social loss. Sichuan had the lowest environmental external cost among the four provinces, resulting in a relatively smaller environment-adjusted net loss. From the perspective of total social cost composition, environmental external cost dominated the economic burden of soybean production. The proportion of environmental external cost in total social cost reached 86.28% in Heilongjiang, 92.35% in Hubei, 91.06% in Shandong, and 88.66% in Sichuan. This indicates that most of the social costs were not directly reflected in farmers' production expenses but were associated with environmental damages throughout the soybean life cycle.

After incorporating environmental external costs, all four provinces showed negative environment-adjusted net incomes. This result does not indicate that farmers experienced negative operating income in all regions; rather, it reflects that the market value generated by soybean production was insufficient to compensate for both direct production costs and environmental damages from a societal perspective. The gap between producer income and environment-adjusted income highlights the influence of environmental externalities in soybean production. As shown in **Figure 7**, the total output value was substantially lower than the total social cost in all provinces, explaining the negative environment-adjusted net incomes. Taking Shandong as an example, although it achieved a producer net income of 6147 yuan/hm^2 with the highest output value (19,443 yuan/hm^2), its total social cost reached 148,746 yuan/hm^2, resulting in an environment-adjusted net income of −129,303 yuan/hm^2. Similarly, Hubei achieved the highest producer net income, but its high environmental external cost (119,726 yuan/hm^2) led to an environment-adjusted net income of −113,535 yuan/hm^2. Sichuan showed the smallest environment-adjusted loss due to its relatively low environmental external cost, whereas Heilongjiang faced combined pressure from negative producer income and considerable environmental costs.

Regarding the composition of environmental external costs, GWP and LOP were the dominant contributors, together accounting for approximately 90% of the total external cost. This indicates that greenhouse gas emissions and land occupation were the main factors determining the environmental economic burden of soybean production. Other impacts, including fossil resource consumption, particulate matter formation, eutrophication, and ecotoxicity, contributed smaller but still relevant shares.

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Overall, the results demonstrate that environmental external costs were mainly driven by climate-related impacts and land resource occupation, which substantially influenced the difference between producer-oriented economic performance and environment-adjusted economic outcomes.

4. Discussion

The results of this study show that the environmental and economic performance of soybean cultivation was not fully consistent among the four provinces. Shandong and Hubei achieved relatively high producer incomes; however, they also showed higher environmental external costs. This finding indicates that higher economic returns do not necessarily represent better environmental-economic performance.

Similar trade-offs between agricultural profitability and environmental burdens have been reported in previous studies, where intensive production systems often achieve higher economic outputs at the expense of increased resource consumption and environmental impacts [24]. Heilongjiang, as a traditional major soybean-producing province, showed high production costs and negative producer net income. This result suggests that production advantages alone cannot guarantee profitability when cost increases exceed economic returns. In this study, green soybean production is considered as a system that achieves relatively low environmental burdens while maintaining acceptable economic performance. Since a unified quantitative benchmark for optimal soybean production in China is currently unavailable, the province with the lowest environmental burden among the evaluated regions was used as a relative reference. Sichuan showed the lowest normalized environmental impact index and environmental external cost, representing a relatively favorable environmental performance within the studied provinces. Compared with this reference level, Shandong and Hubei showed higher environmental burdens mainly due to processing-related impacts and external environmental costs, while Heilongjiang faced combined challenges from economic and environmental pressures.

The life cycle stage analysis indicated that processing activities, especially by-product processing, refining, and main-product processing, were important contributors to soybean environmental impacts. This finding suggests that soybean sustainability improvement should not focus only on field management but should also consider downstream processing. Previous LCA studies have also emphasized the importance of processing energy consumption and by-product utilization pathways in determining the environmental performance of agricultural products [25]. Therefore, improving processing efficiency and optimizing energy use may provide opportunities for reducing life cycle environmental burdens.

The environmental impact category analysis showed that GWP, LOP, and FETP were important contributors to the environmental burden of soybean production. These results are consistent with previous agricultural LCA studies showing that energy consumption, land occupation, and agricultural inputs are major drivers of environmental impacts [26]. The environmental risk contribution analysis further revealed that air- and soil-related impacts dominated the environmental external cost structure, accounting for more than 94% of the total external cost. Because atmospheric emissions are closely associated with environmental quality and potential health risks, reducing emissions from agricultural inputs and processing activities may provide additional environmental benefits [27].

The results also indicate that improvement pathways should consider regional differences. For Shandong and Hubei, where economic returns were relatively high, but environmental costs were also considerable, improving processing efficiency and reducing energy-related emissions may help achieve better environmental-economic coordination. For Heilongjiang, improving input-use efficiency and reducing cost intensity are important for alleviating economic pressure. For Sichuan, increasing yield and economic returns while maintaining its relatively favorable environmental performance may provide opportunities for further improvement.

5. Limitations and Future Prospects

Although this study provides a comparative assessment of soybean cultivation in four provinces from both environmental and economic perspectives, several limitations remain. The first limitation lies in the life cycle inventory data. Some input data were based on a general inventory or scaled according to yield, so they may not fully capture the actual processing technologies, energy structures, and management practices in different provinces. In future research, more detailed first-hand data could be collected from processing enterprises, farmers, and cooperatives to improve the accuracy of the inventory.

Another source of uncertainty comes from the monetization of environmental external costs. The external cost results depend on the selection of environmental damage cost coefficients. If different coefficients are used, the absolute values of external costs may change. Therefore, future studies should include sensitivity analysis and uncertainty analysis to test whether the ranking of provinces and the main conclusions remain stable under different parameter settings.

In addition, this study mainly used 1 hm^2 of soybean cultivation and subsequent processing as the functional unit. This setting is useful for linking environmental results with economic return data. However, it does not directly compare the environmental efficiency of soybean products. Future research could further calculate the environmental impacts per kilogram of soybean grain or per kilogram of refined soybean oil. This would provide a clearer basis for comparing production efficiency and product-level environmental footprints among provinces. And soil organic carbon (SOC) changes were not included because long-term site-specific SOC data were unavailable for the selected provinces. Future studies incorporating dynamic soil carbon models could provide a more comprehensive evaluation.

The environmental-economic coupling analysis in this study was mainly discussed through environmental impacts, producer income, total social cost, and environment-adjusted net income. A quantitative coupling coordination model was not further developed. Future research could construct a coupling coordination degree index by standardizing environmental and economic indicators. This would make it possible to measure the coordination level of soybean cultivation in different provinces more directly and to identify the main factors driving regional differences.

6. Conclusions

This study integrated life cycle assessment and life cycle cost analysis to evaluate the environmental burdens and economic performance of soybean cultivation in Heilongjiang, Hubei, Shandong, and Sichuan. The results revealed substantial regional differences in both environmental impacts and economic returns, demonstrating that environmental performance and producer profitability were not always consistent across different production systems.

From the environmental perspective, the life cycle impacts of soybean cultivation were mainly concentrated in the processing stages, particularly by-product processing, refining, and main-product processing, indicating that environmental improvement should extend beyond field management to include cleaner processing technologies and more efficient by-product utilization. Among the environmental impact categories, freshwater ecotoxicity made the largest contribution to the normalized environmental impacts, highlighting the importance of reducing emissions associated with agricultural inputs and processing activities.

The environmental risk contribution analysis showed that air- and soil-related impacts were the main contributors to environmental external costs, accounting for more than 94% of the total external cost across the four provinces. By comparison, the contributions from water-related impacts, resource depletion, and human health impacts were relatively small. This pattern suggests that atmospheric emissions and soil-related environmental pressures were the primary factors influencing the environmental external cost of soybean production.

From the economic perspective, Hubei and Shandong showed relatively higher producer returns, whereas Sichuan had limited profitability and Heilongjiang experienced negative producer net income. However, when environmental external costs were included in the economic assessment, all four provinces showed negative environment-adjusted net income. This result suggests that the economic value generated by current soybean production systems does not fully compensate for the environmental costs associated with their life cycle impacts, emphasizing the need to consider environmental externalities alongside conventional economic indicators. Overall, soybean cultivation exhibited distinct environmental-economic characteristics among the four provinces, suggesting that region-specific improvement strategies are required. Future efforts should focus on reducing energy consumption during processing, optimizing agricultural input management, improving the efficiency of by-product utilization, and promoting policy instruments such as ecological compensation and green incentives. These measures will contribute to improving the environmental-economic coordination and long-term sustainability of soybean production in China. Moreover, the findings provide scientific evidence for developing agricultural management strategies that can simultaneously reduce environmental burdens, mitigate potential environmental health risks, and support sustainable agricultural development.

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