

Article

Integrated Horticultural Practices for Improving Apple Supply Chain Sustainability: A Case Study in the North China Plain

Shan Jiang, Chen Yang, Yu Guo and Xiaoqiang Jiao *

National Academy of Agriculture Green Development, Department of Plant Nutrition, China Agricultural University, Beijing 100193, China; sy20193030374@cau.edu.cn (S.J.); yangchen180620@163.com (C.Y.); gywasaicau@126.com (Y.G.)

* Correspondence: xqjiao526@126.com

Abstract: Apple production provides smallholders with low economic benefits, while high environmental emissions limit the sustainability of the apple supply chain. Furthermore, coordination to achieve greater economic benefits and environmental protection, thereby improving the sustainability of the apple supply chain, remains underdeveloped. Here, we have analyzed the current status of the economic benefits and environmental emissions of the apple production process and explored the level of collaboration within the apple supply chain, based on an analysis of farmer horticultural practices for high production, high economic benefit, and low environmental emissions, in combination with substance flow analysis. Our study showed that compared with traditional practice, high-yielding, high-efficiency practice allowed fruit yield, partial productivity of nitrogen fertilizer, and economic benefit to increase by 33%, 61% and 49%, respectively, while soil nitrogen residue levels decreased by 13%. The improvement and adoption of technology in the apple-planting process significantly improved the sustainability of the apple supply chain: the economic benefit increased by 63%, while the nitrogen footprint decreased by approximately 68%. Additionally, the application of integrated nutrient management technology in the apple planting process significantly improved the sustainability of apple production, thereby synergistically improving the economic and environmental impact of the apple supply chain.

Keywords: high yield and high efficiency; apple; supply chain; substance flow analysis (SFA); nutrient management; N flow; economic benefits



Citation: Jiang, S.; Yang, C.; Guo, Y.; Jiao, X. Integrated Horticultural Practices for Improving Apple Supply Chain Sustainability: A Case Study in the North China Plain. *Agronomy* **2021**, *11*, 1975. <https://doi.org/10.3390/agronomy11101975>

Academic Editors: Riccardo Testa, Giuseppina Migliore, Giorgio Schifani and József Tóth

Received: 2 August 2021

Accepted: 19 September 2021

Published: 30 September 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The apple tree is a perennial deciduous species of the genus *Malus*, within the subfamily *Malus* of the Rosaceae family. Apples are rich in a variety of minerals and vitamins and have a high nutritional value. Furthermore, they are one of the four major fruits (apples, bananas, citrus, and pears) produced in China. Thus, Chinese total apple output in 2019 was 42.4 million tons, accounting for 36.2% of the total output of these major fruits [1,2]. Indeed, China is currently the largest apple cultivator and producer in the world, as well as a significant apple exporter. Consequently, apples are one of the most important cash crops in China [3] and play a vital role in the endeavors of smallholders to overcome poverty and become economically independent, improving rural economic conditions, and increasing the level of industrialization [4]. However, in pursuit of raising the output of apple cultivation, smallholders tend to use excessive amounts of fertilizers to maximize economic benefit. This extensive management strategy has led to a wasteful use of nutrient resources, causing a series of environmental problems that have severely limited the sustainability of the apple supply chain, such as groundwater nitrate pollution and soil acidification [5]. As in many others, the apple supply chain consists of many different links, including apple planting, apple processing, apple selling and distribution. Fruit supply-chain management is more complex than other food supply chains because it has unique characteristics, including storage-life considerations, the security and volatility of demand and price,

inventory, production, and distribution [6]. Previous research on the apple supply chain mainly focused on post-harvest handling; however, the agricultural input and production process thereof, before harvest, have rarely been analyzed to any detail [7,8]. Thus, for example, in one of the few previous studies available, Soto-Silva et al. (2017) proposed an optimization model for decision-making related to the purchasing, transportation, and storage of fresh agricultural products [8]. In turn, Paam et al. (2019) studied the impact of inventory management optimization on fruit loss, inventory, and processing costs in an apple supply chain [7]. Lastly, Khan et al. (2016) determined that the income of producers in the Pakistani apple supply chain was 27%, while that of intermediaries was as high as 73% [9].

While apple production is the main stage in the apple supply chain, apple production in China currently faces many difficult challenges, such as low yields, poor quality, low export volume, over-large scale, irrational variety structure, and significant variation in yield and resource utilization efficiency among orchards [10,11]. As the main players in apple production, smallholders have limited resources, low educational levels, and a low availability of technological inputs; such that they often resort to insurance strategies for nutrient management due to the limitations imposed by poor training, the influence of traditional concepts, the lack of agricultural extension services, and the misleading influence of fertilizer retailers. Together, these factors have led to excessive fertilization, such that nutrient input is much greater than crop requirements, whereby, improving the capacity of smallholders for apple production and rational nutrient management are key issues for increasing the economic and environmental benefits of the apple supply chain [12].

Numerous studies have shown increased production efficiency of apple trees. For example, Ge et al. (2017) reviewed currently available technologies for reducing apple fertilizer input while increasing fertilizer-use efficiency, mainly focusing on obstacles in soil improvement and fertility enhancement, optimal nutrient management, root layer nutrient regulation, and new fertilizers and “large formulas, small adjustments” [13]. In turn, Sun et al. (2018) conducted field trials over three consecutive years and found that the optimum depth for manure application was 20–40 cm, and that the optimum application rate was $75 \text{ m}^3 \cdot \text{hm}^{-2}$, as it had the best effect on the growth, yield, and fruit quality of new apple shoots [14]. Most current research focuses on the effect of horticultural practices on a single stage and a single goal of and for the apple supply chain, while research on the multi-objective coordination of the apple supply chain is lacking, especially on how to achieve economic and environmental synergy within the supply chain. The disclosure of this information, while determining the localization technology of sustainable apple production, can also be of significance for smallholders in terms of optimizing resource utilization, improving resource utilization efficiency, achieving greater economic benefits, and reducing environmental emissions throughout the apple supply chain.

Therefore, in this study, we analyzed 66 smallholders in Quzhou County, a typical apple production area in the Bohai Bay region of the North China Plain. Our goals were: (1) to analyze the economic benefits and environmental emissions generated during apple planting/processing/sales, and (2) to clarify comprehensive horticultural practices to synergistically increase the economic benefits of the apple supply chain while reducing environmental emissions associated, and ways to sustainably improve the supply chain based on the analysis of different types of farmers.

2. Materials and Methods

2.1. Overview of the Research Area

The study area is located in Xianggongzhuang Village, Quzhou County, Hebei Province ($36^{\circ}46' \text{ N}$, $115^{\circ}1' \text{ E}$). The site is located in the Heilongjiang Basin of the Haihe Plain on the eastern foot of Taihang Mountain in the southern Hebei Province. It is in the upper Zhanghe alluvial fan in the Heilonggang area at the intersection of the alluvial plains of the Zhang and Fuyang rivers and the alluvial plains of the Yellow River. The region is characterized

by a warm temperate, semi-humid, continental monsoon climate and an annual average temperature of 13.1 °C and an annual average rainfall of 556.2 mm. Precipitation is concentrated in July–September, and rain and heat arrive simultaneously, which is beneficial for agricultural production; however, it is dry and windy in spring. The soil is mainly composed of clay. Xianggongzhuang Village is the largest apple-growing village in Quzhou County. There are >120 ha of apple planting land, accounting for approximately 52.9% of the total apple-cultivated area in the county, and 64.0% of the arable land in the village. Apple cultivation in Xianggongzhuang Village has promoted the development of the apple industry in the surrounding areas and, indeed, in the entire county. However, owing to the different characteristics of farmer types present and their different agronomic training, among other reasons, apple yield and quality vary substantially among different local farmers.

2.2. Farmer Survey

Our survey included the following five aspects. (1) Sample selection: 70 growers were randomly selected for questionnaire surveys among more than 210 apple growers in Xianggongzhuang Village, Quzhou County; 66 valid questionnaires were obtained, covering an area of 15.0 hm², which accounted for approximately 12.5% of the local planting area. (2) Questionnaire design: this mainly included gathering basic farmer information, such as gender, age, educational level, apple variety planted, tree age, orchard tree-population density, etc., orchard management practices, such as fertilization application, fertilization period, fertilization type, irrigation frequency, time and frequency of pesticide application, use of a swelling agent, the amount of reflective film used, bagging period, number of bags, and other information items. (3) Implementation of the survey: the survey was conducted from July to September 2020; surveyors completed the questionnaire while asking questions; (4) Data revision: Due to the limited knowledge of farmers, their understanding of fruit tree management, and the degree of cooperation in research work, the data and information obtained in the survey may be different from the actual situation. To obtain information on yield and details on horticultural practices, the question-and-answer approach was utilized. After conducting the survey, the data were standardized and revised, and if necessary, a return visit was conducted via telephone. Through visits with 10 apple purchasers and three supermarkets in Quzhou County, apple wholesale and retail prices were collected.

The distribution of the indicators of the 66 smallholders in this survey is shown in Figure S1. The surveyed orchard trees were 5–30 years old. Forty-five smallholders (68.2%) possessed orchards < 15 years old (Figure S1a). The orchard area was 0.05–1.33 hm², of which 40 smallholders (60.6%) possessed orchards < 0.20 hm², and there were only five (7.6%) orchards > 0.40 hm² (Figure S1b). The distribution of organic N application rates of smallholders showed a U-shaped trend; 27 (40.9%) smallholders use an application rate of 0–200 kg·hm^{−2}, and 11 smallholders use > 1200 kg·hm^{−2}. There were 9, 3, 4, 3, 9, 11 smallholders who use application rates of 200–400, 400–600, 600–800, 800–1000, 1000–1200, and >1200 kg·hm^{−2}, respectively (Figure S1c). However, the application of N fertilizer by smallholders is mainly concentrated in the range of 200–800 kg·hm^{−2}, accounting for 71.2% (Figure S1d) of all growers surveyed.

2.3. Composition of the Apple Supply Chain in Quzhou County

The research framework and system boundaries of this study are shown in Figure 1. The apple supply chain is divided into three stages: pre-production, production, and post-production. Commercial agricultural inputs (chemical fertilizers, commercial manure, pesticides, reflective films, etc.) and livestock manure produced in the breeding process are transported into the orchard, and the producers follow a series of horticultural and soil management practices to obtain better planting procedures. Finally, apples enter the market through acquisitions, retail, or picking gardens, while bad fruit is returned to the fields or disposed of.

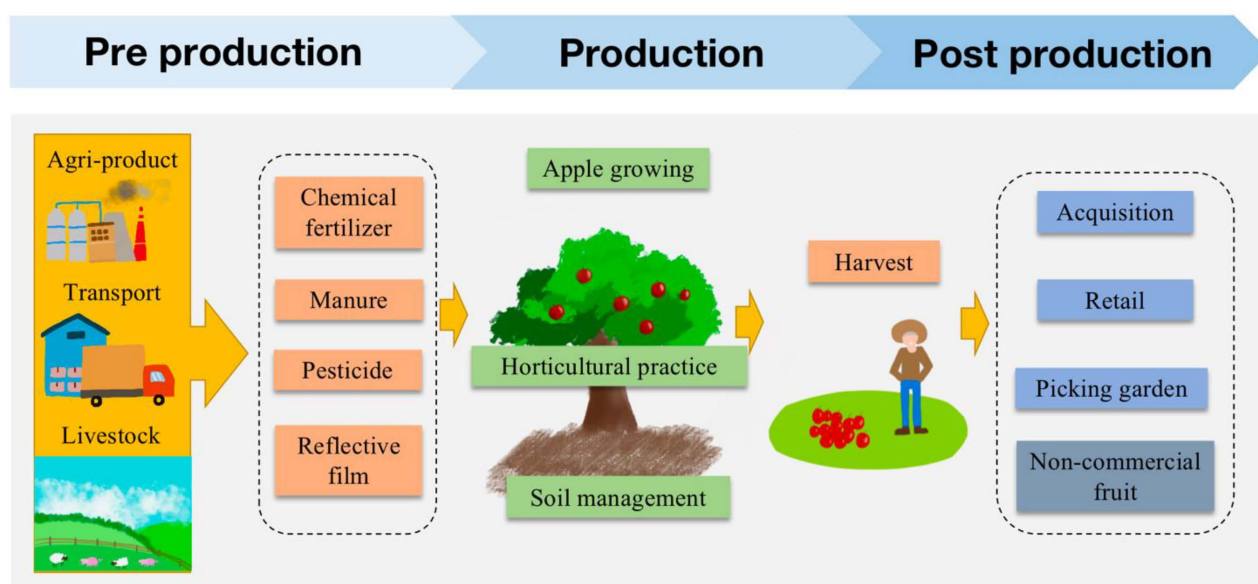


Figure 1. Research framework and system boundaries.

2.4. Data Calculation

2.4.1. N Flow, N Loss, and N-Use Efficiency

The substance flow analysis (SFA) method is used to analyze N flow, N loss, and N use efficiency (NUE) in the apple supply chain system.

N flow: The source of N was determined according to the research situation, and the relevant parameters of the location of ammonia volatilization, denitrification, and soil residual were determined by referring to the literature (Table S1). N input, N loss, and N output were calculated. A Sankey diagram was used to clarify the source and location of N entering the system. The N footprint and NUE were then calculated using the following equations:

$$N_{input} = I_1 + I_2 + I_3 + I_4 + I_5, \quad (1)$$

$$N_{output} = O_1 + O_2, \quad (2)$$

$$N_{loss} = N_{input} - N_{output}, \quad (3)$$

$$N \text{ footprint} = N_{input} / (O_1 - E_5) \quad (4)$$

$$NUE = (O_1 - E_5) / N_{input}. \quad (5)$$

Supplementary Table S1. Where N input is the total nitrogen input, I_1 is the N input as chemical fertilizer, I_2 is the N input as manure, I_3 is the biologically fixed N, I_4 is the atmospheric deposition of N, I_5 is the irrigation water N, N output is the total output of N, O_1 is the N content in the apple fruit, O_2 is the N content in the apple tree (trunk, branches, and leaves), N loss is the loss of nitrogen, E_5 is bad fruit, and N is low-quality apple yield.

2.4.2. Partial Productivity of Fertilizer

Partial Productivity of Fertilizer (PPF-N) is one of the indicators for smallholders' classification, and the other is yield.

$$PPF-N = Y / F_N \quad (6)$$

where, PPF-N is the partial productivity of N fertilizer ($\text{kg} \cdot \text{kg}^{-1}$), Y is the apple yield ($\text{kg} \cdot \text{hm}^{-2}$), and F_N is the N input ($\text{kg} \cdot \text{hm}^{-2}$).

The nutrient content of chemical fertilizers was calculated according to the standard nutrient content of the fertilizer, or the nutrient content marked in the fertilizer bag; meanwhile, manure was converted according to the manure nutrient content in Appendix 2

of the Guide to Fertilization of Major Crops in China (2009) [15], and expressed by the amount of converted pure nutrient.

2.4.3. Data Processing and Statistical Analysis

Data were collated, calculated, and plotted using Microsoft Excel 2010, e! Sankey (Version 4.1, Hamburg, Germany), and Origin 9.1 (Version 12.0, Systat Software Inc., San Jose, CA, USA). We conducted an independent sample *t*-test analysis of the test results using IBM SPSS statistics (Version 25, Chicago, CA, USA) and compared the significance of differences among treatments ($p < 0.05$).

3. Results

3.1. Classification and Screening of Smallholders

Our study was based on 66 smallholders, among whom, 17 high-yield and high-efficiency (HYHE) apple growers were selected using the quartet method, i.e., farmers whose fruit yield and PFP-N were both above the average of the 66 smallholders (Figure 2). The remaining three categories of farmers were high-yield, low-efficiency smallholders, low-yield high-efficiency smallholders, and low-yield low-efficiency smallholders, with sample sizes of 16, 8, and 25, respectively. We defined these three types of farmers as those following traditional practices (TPs).

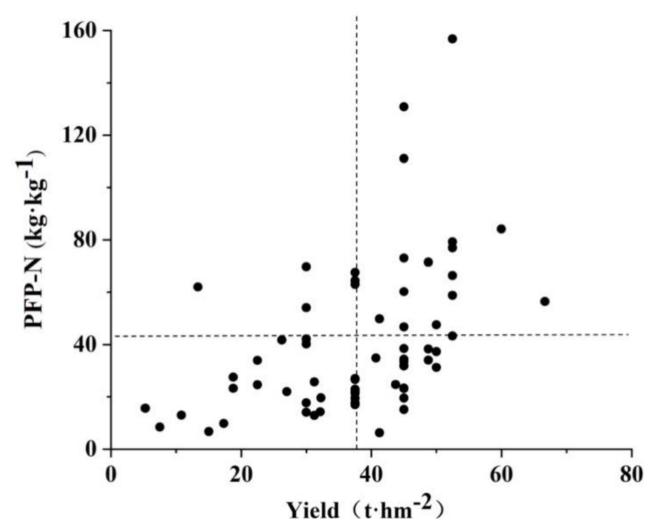


Figure 2. Distribution of the surveyed smallholders as per yield and partial productivity of the fertilizer (PFP-N). The dotted line in the figure represents the average yield and PFP-N.

In the planting stage, average apple yield of HYHE farmers was $50.3 \text{ t} \cdot \text{hm}^{-2}$, PFP-N was $29.3 \text{ kg} \cdot \text{kg}^{-1}$, and the economic benefit was $78,262.5 \text{ 184 CNY} \cdot \text{hm}^{-2}$, and the N footprint was $3.06 \text{ kg} \cdot \text{kg}^{-1}$, which were 33.4%, 61.2% and 48.8% higher than those of TPs. The N footprint was $3.06 \text{ kg} \cdot \text{kg}^{-1}$, which was 67.6% lower than the average TP level (Figure 3).

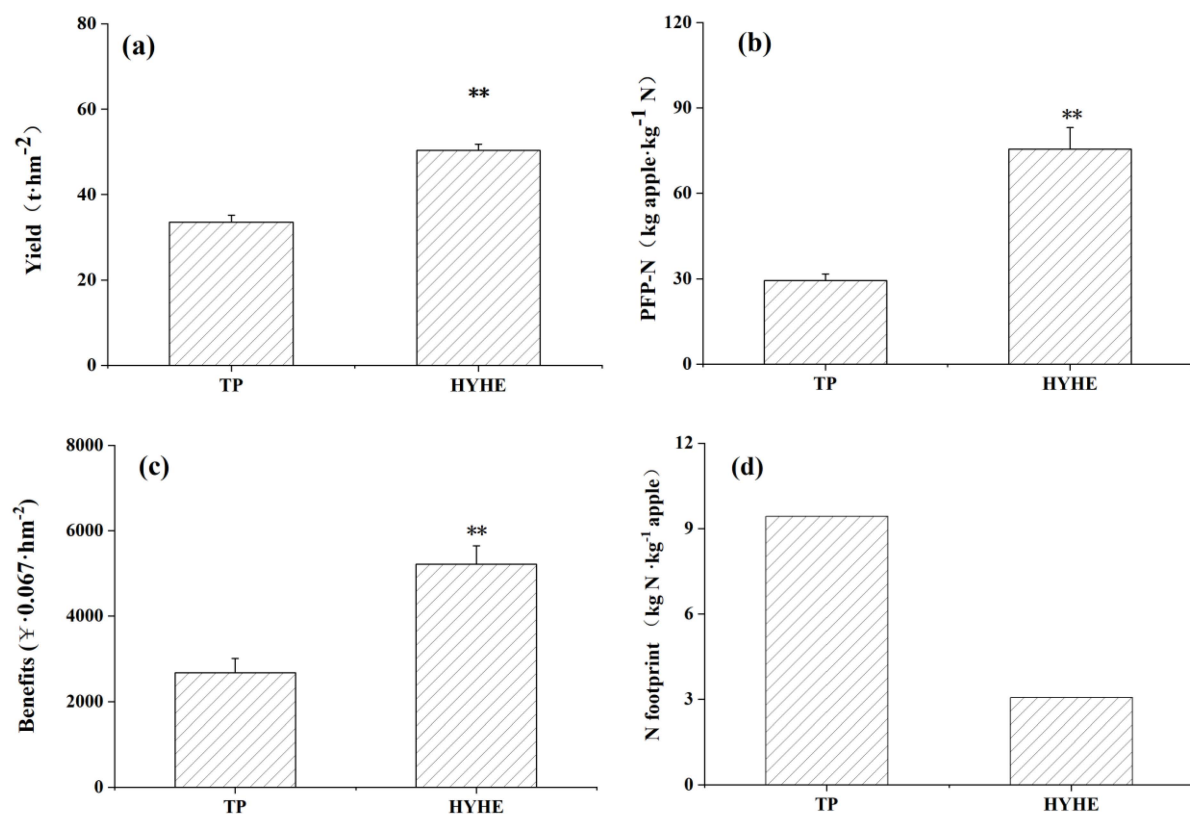


Figure 3. Comparison of indicators between traditional producers (TP) and high-yield high-efficiency (HYHE) farmers. (a) Yield, (b) PFP-N, (c) economic benefits, and (d) N footprint. ** $p < 0.01$.

3.2. Differences in Horticultural Management

On comparing the horticultural practices of the two groups, fertilizer N, P_2O_5 , and K_2O input among farmers in the HYHE group was lower than those of the TP's group by 48.6%, 52.8%, and 45.1%, respectively, and the fertilizer application was more concentrated. The N and K_2O inputs of the two groups differed significantly ($p < 0.01$); similarly, P_2O_5 input was also significantly different ($p < 0.05$). The frequency of pesticide use in the HYHE group was 9.7% lower than that in the traditional farmer group, and the amount of reflective film was 36.3% higher among farmers in that group than among their counterparts in the latter (Figure 4).

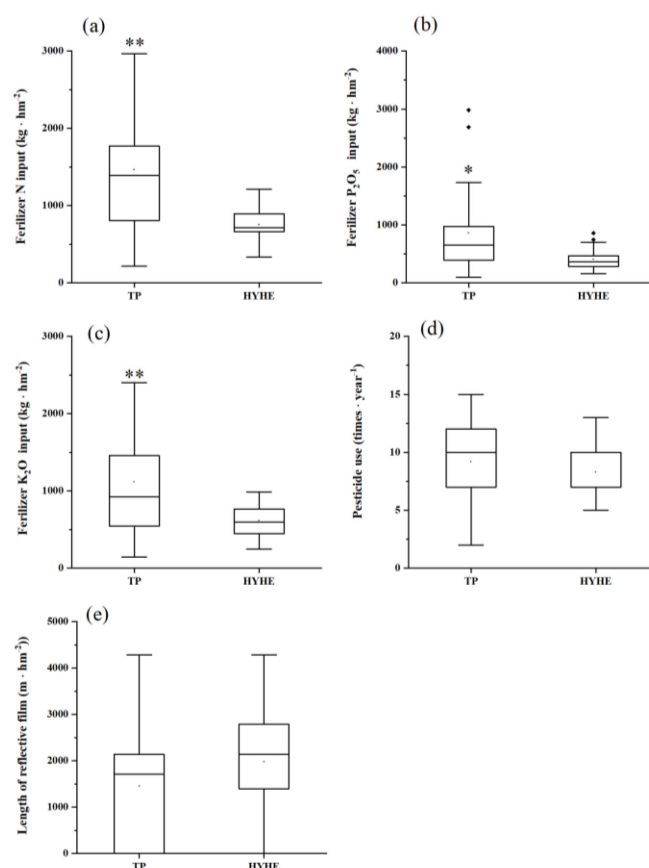


Figure 4. Comparison of indicators between traditional and HYHE farmers. (a) Fertilizer N application; (b) fertilizer P_2O_5 application; (c) fertilizer K_2O application; (d) pesticide use; (e) length of reflective film. * $p < 0.05$; ** $p < 0.01$.

3.3. N Input and Flow in the Apple Supply Chain

The N flows of the HYHE and TP groups were different. In the TP group of farmers, total N input was $1538.6 \text{ kg} \cdot \text{hm}^{-2}$, of which 48.7% was provided as chemical fertilizer and 46.5% as manure; the average fruit yield was $33.5 \text{ ton} \cdot \text{hm}^{-2}$, and the apple fruit contained $189.8 \text{ kg N} \cdot \text{ton}^{-1}$. During harvest and the sale process, apples with mechanical damage by insects, diseased fruit, out-of-range fruit, color defects, etc., will not be sold, whereby, 9.5 kg of N is lost. The final edible apple fruit contained 180.3 kg of N, which accounts for only 11.7% of the N input. Additionally, N losses in the form of NH_3 and N_2O were 51.0 kg and 11.9 kg, respectively, and 21.3% of the N applied remained in the soil (Figure 5a).

As for the HYHE group of farmers, total N input was $826.8 \text{ kg} \cdot \text{hm}^{-2}$, which was 46.3% lower than the N input in the case of traditional farmers. The use of chemical fertilizer N was reduced by 26.6% and the use of manure N was reduced by 71.7%. The residual N in the soil was reduced to $286.1 \text{ kg} \cdot \text{hm}^{-2}$ (Figure 5b). Concomitantly, NH_3 and N_2O emissions were reduced by 39.4% and 48.7%, respectively (Figure 5).

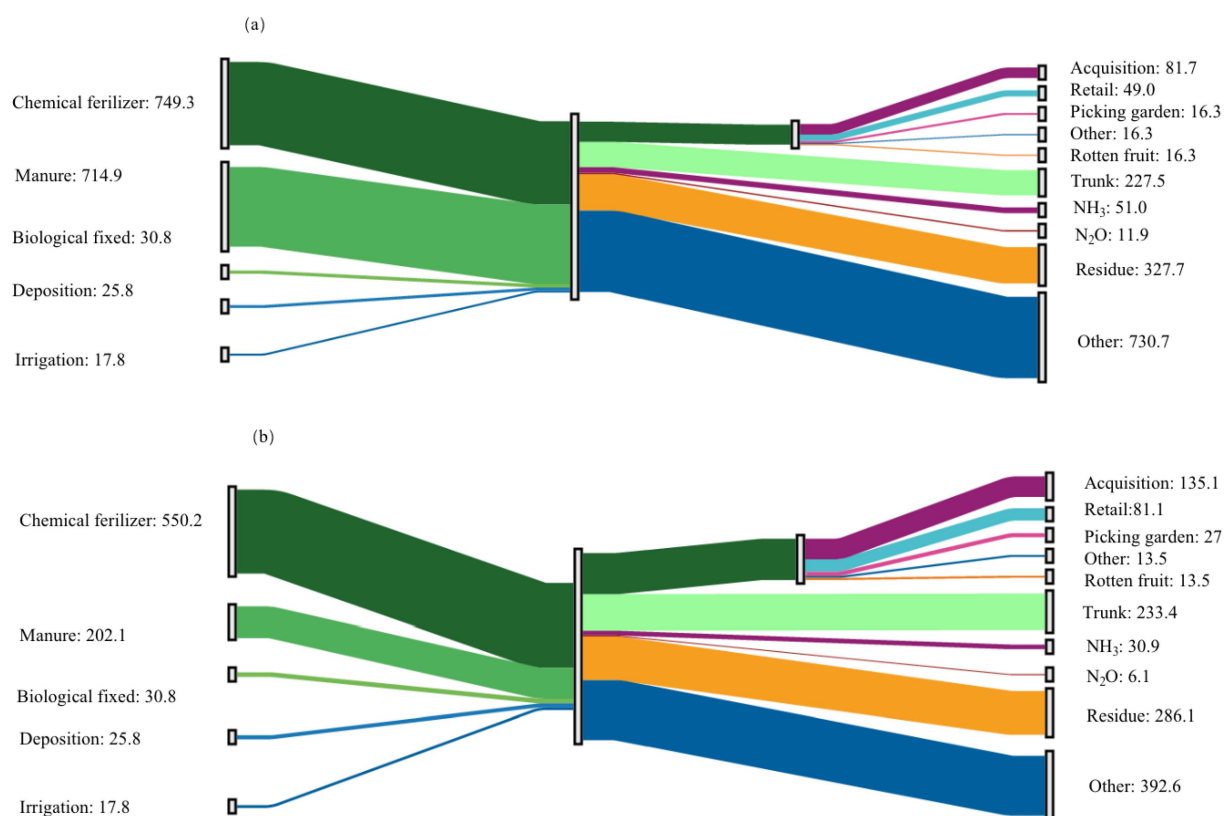


Figure 5. N flow (kg·hm⁻²) in apple orchards. (a) N flow (kg·hm⁻²) in orchards of TP farmers; (b) N flow (kg·hm⁻²) in orchards of HYHE farmers. The data were based on our 2020 survey of 66 farmers in Xianggongzhuang Village, Quzhou County, Handan city, Hebei Province. The quarter method was used to evaluate 17 apple orchards run by HYHE farmers.

3.4. Promoting Effect of Horticultural Practices on Economic Benefits from the Apple Supply Chain

Consumers obtain apples through three links: apple production, apple processing, and apple sales. There are several pathways that may link farmers and consumers, including retail (farmer–consumer), acquisition (farmer–acquirer–supermarket–consumer), and picking gardens (farmer–consumer). In the supply chain run by the TP group of farmers, the profit of smallholders accounted for only 36.4% of the total profit, while in the supply chain run by farmers of the HYHE group, the profit of smallholders accounted for 41.8% of the total profit. Nonetheless, although smallholders were the most important participants in the apple supply chain, in both cases, for every hectare of apples planted, the economic benefits obtained were lower than those obtained by the acquirer and the supermarkets. Our findings suggest that the planting process of the apple supply chain can be optimized through improved horticultural practices, such as the optimization fertilizer application, the reduction of pesticide application and better pest-damage control, and by increasing the use of reflective film. After optimizing the planting process through these horticultural practices, the economic benefits of the apple supply chain increased by 63.0%, the economic benefits of smallholders increased by 87.2%, and the economic benefits of acquirers and supermarkets increased by 49.1%. Consistently, HYHE production strategies improved the economic benefits obtained by farmers to an even greater extent (Figure 6).

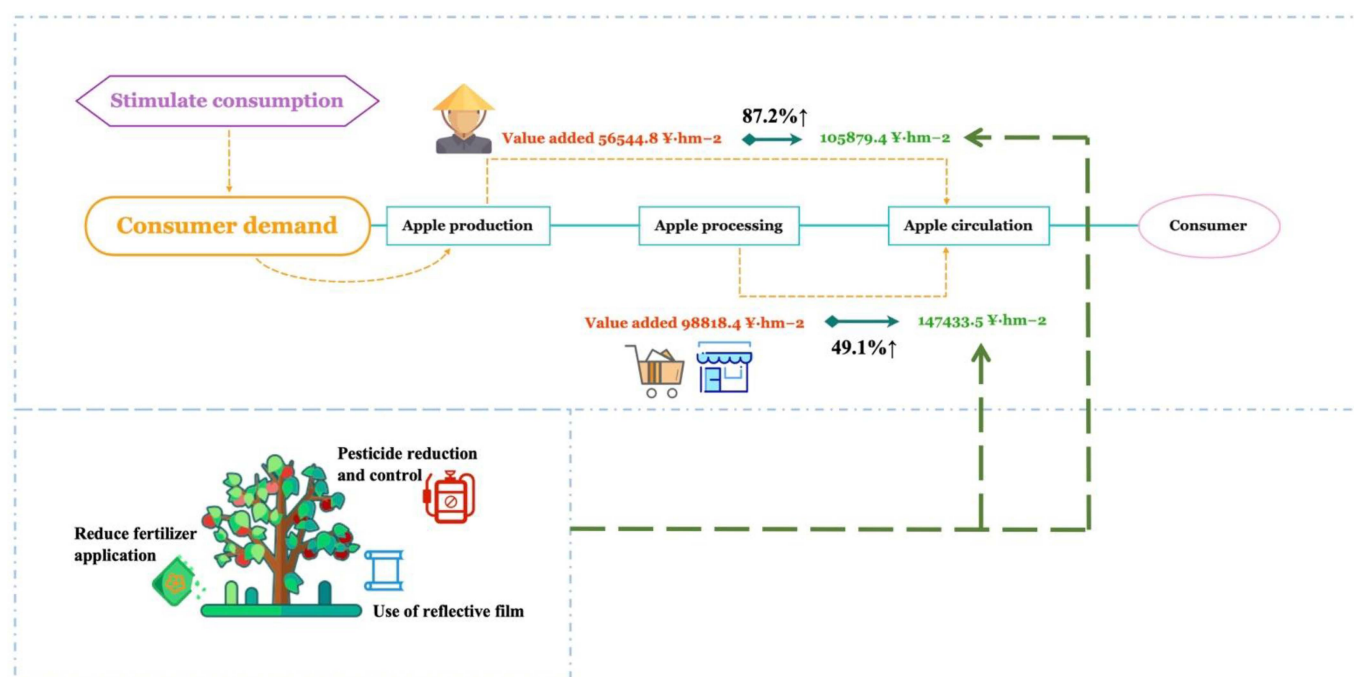


Figure 6. Economic benefits of the apple supply chain and the effect of HYHE horticultural practices on economic benefits.

4. Discussion

4.1. Smallholders with High Yield and High-Efficiency Apple Production Potential and Localization Technology

A remarkable result of this study is the utilization of a farmer-optimization method combined with substance flow analysis (SFA) to explore the potential for sustainable production and localization technology of apple orchards in the hands of smallholders. Compared with the TP group of farmers, 17 HYHE smallholders increased their apple output by 33.4%, PFP-N increased by 61.2%, and economic benefits increased by 48.8%. This was mainly accounted for by the adoption of HYHE technologies; namely, optimizing the use of chemical fertilizers and applying manure, reducing pesticide input, and increasing the use of reflective films (Figure 6). The adoption of these technologies enabled the nutrient supply in the rhizosphere of the apple orchards and the aboveground nutrient demand to achieve spatiotemporal and quantitative matching. To ensure high yield and high output value, smallholders and researchers should promote HYHE apple-production schemes while reducing environmental costs [16]. Our results showed that there remains much room for the improvement of apple production by smallholders in Quzhou. Additionally, adopting the farmer selection method also facilitates the localization of technology for high-yield and efficient smallholders to achieve sustainable production.

This research has constructed a comprehensive analytical technology that focuses on N reduction and combines multiple horticultural practices. HYHE smallholders mainly adopted technologies such as reducing chemical fertilizers, optimizing the application of manure, increasing the use of reflective film, and reducing pesticide inputs. The excessive application of chemical fertilizers is one of the main limiting factors for achieving HYHE in apple production [17]. Indeed, reducing the amount of N fertilizer in apple production may potentially improve N fertilizer-use efficiency, and has great significance for environmental protection [18,19].

By and large, apple production in the Bohai Bay region is in the hands of smallholders whose lack of high training and expert knowledge often leaves no recourse but to use insurance to increase their apple production [20]. Nonetheless, optimization of N fertilizer is crucial to improving the sustainability of apple production. However, the production of apples is a complex process, and the application of other measures must be combined with

the optimization of N fertilizer to realize the construction of localization technology. Thus, for example, Wang et al. (2017) found that reflective films can improve light conditions, regulate the soil microenvironment, and improve the quality of citrus by affecting tree growth and photosynthesis [21]. Similarly, Zhang et al. (2020) found that the use of reflective film in orchards can significantly increase vitamin C content and coloring degree of apples while reducing titratable acid content and increasing redness [22]. Manure can increase soil microbial populations and balance soil microbial communities. Therefore, the combined application of manure and chemical fertilizers can increase the content of soil's organic matter [23,24]. Consistently, Gong et al. (2019) found that the application of organic fertilizer ($75 \text{ kg} \cdot \text{plant}^{-1}$) in apple orchards has a better effect on improving overall soil fertility [25]. Soil organic matter, available nutrients (alkali nitrogen, available potassium), soil enzyme activities (sucrase, urease), and other indicators are also improved upon organic fertilizer application. Taking the 0–20 cm soil layer as an example and compared with the control group ($0 \text{ kg} \cdot \text{plant}^{-1}$), soil organic matter, alkali nitrogen, available potassium, and sucrase and urease activities increased by 37.89%, 65.80%, 25.90%, 21.92% and 115.15%, respectively. Clearly, the adoption of these comprehensive nutrient-management technologies improved the sustainability of apple production.

Nevertheless, the localization technology explored in this research still lags behind international standards. Our conclusions are based on survey data obtained from farmers that provide strong evidence for the need to explore localization technology; however, the optimization technique is based on the extensive horticultural practices of farmers in the TP group. Therefore, the nutrient input of HYHE smallholders is likely still excessively high. In a 2017 survey, Ge et al. [13] demonstrated that the fertilizer application of apple production in developed countries globally is generally low, and the recommended application rates of N, P_2O_5 , and K_2O are 150–200, 100–150, and 150–200 $\text{kg} \cdot \text{hm}^{-2}$, respectively, which are much lower than the actual fertilization rates commonly used in Xianggongzhuang. Even the HYHE farmers in this study accumulated 286.1 $\text{kg} \cdot \text{hm}^{-2}$ in their orchard soils (Figure 5b), which is equivalent to the annual N application in apple orchards in developed countries. In a study conducted in 2018, Chen et al. [26] found that when the annual N application rate in apple orchards was 200 $\text{kg} \cdot \text{hm}^{-2}$, the photosynthetic capacity, fruit tree growth, and fruit quality were better than those obtained with an annual N application rate of 300 $\text{kg} \cdot \text{hm}^{-2}$. Similarly, Kumar et al. (2016) supplied fruit trees with 70 g of N each. Then, comparing different fertilization rates and fertilization methods, they found that 80% fertilization not only saved 40% of water and 20% of fertilizer by reducing fertilization and drip irrigation but additionally, improved productivity and ensured higher fruit quality in their sample [27].

4.2. Effect of Localization Technology on High-Yield and Efficient Apple Production through the Supply Chain

Another remarkable result of this research is the evaluation of the impact of localization technology on the sustainability of the apple supply chain. Previous studies were mostly field experiments, single factor or farmer surveys that were not combined with other subjects. This research not only built a localization technology but additionally, it clarified its impact on the efficiency of the entire supply chain.

In this study, the corresponding horticultural practices and nutrient management approach have been applied to HYHE smallholders with a yield of $50.3 \text{ t} \cdot \text{hm}^{-2}$. This exceeded the average yields per unit area in the United States and the EU in 2019, which were 39.5 and 26.9 $\text{t} \cdot \text{hm}^{-2}$, respectively [1], and the economic benefit was 5217.5 CNY $\text{t} \cdot 0.067 \text{ hm}^{-2}$ (Figure 3c). However, there is still great potential for yield and income improvement. For example, the highest yield in this survey was $66.7 \text{ t} \cdot \text{hm}^{-2}$, and the highest economic benefit was 166,068 CNY $\text{t} \cdot \text{hm}^{-2}$. Consistently, Wang et al. (2016) showed that improving apple production efficiency and nutrient utilization efficiency can be achieved through a better understanding of the production potential, yield gap, nutrient utilization and optimal management of apple orchards [3].

The supply chain of agricultural products connects the supply of the agricultural means of production, as a whole, and different links involving different stakeholders, such as smallholders, acquirers, and consumers. Problems in any link of the supply chain affect the overall sustainability of the entire chain [28]. Many studies have been conducted on the supply chain and industrial chain of apples. For example, Cai et al. (2017) used the life cycle assessment (LCA) method and found that the input levels of manure and chemical fertilizer were the main factors affecting yield, nutrient use efficiency, energy use efficiency, and comprehensive environmental impact [29]. In turn, Longo et al. (2017) applied the LCA method to clarify that the use of fertilizers and pesticides and the diesel consumption of agricultural machinery are the main reasons for the negative impact on energy and the environment from agricultural production [30]. Paam et al. [7] studied the impact of inventory management optimization on fruit loss, inventory, and processing costs in the apple supply chain. A new policy plan was proposed to provide suggestions for stakeholders in the apple industry to improve their inventory performance. Relieving environmental pressures in the production of different agricultural products is critical for all supply chains. It is necessary to determine a set of feasible interventions, such as technological innovation and improved horticultural practices to enable the environment to sustain consumer demand [31]. In this study, we found that the apple planting process was the key factor limiting the sustainability of the supply chain. Small farmers have invested an wealth of nutrients and labor resources to produce apples; however, they have caused a series of environmental problems and the economic benefits are meager at best. In contrast, the economic benefits in the sales link are 1.5–1.9 times higher than those obtained by farmers in the planting link of the chain.

By promoting the adoption of localization technology by smallholders, synergy can achieve high-yielding and highly efficient apple production systems, thus driving the entire supply chain to achieve economic and environmental coordination. Localization technology, here, improved the sustainability of apple production in the supply chain, resulting in an increase in yield, PFP-N, and economic benefits. However, the mechanisms for sustainably developing an apple supply chain through the in situ implementation of technology warrants further research.

5. Conclusions

In the apple supply chain, horticultural practices, such as optimizing the input of chemical fertilizers, manure, N, P₂O₅, K₂O, pesticide reduction and pest-damage control technology, utilization of reflective films, and other supporting technologies, can be implemented to optimize apple fruit production. Further, the coordinated apple supply chain reduces environmental emissions and improves economic benefits. Compared with the supply chain run by TP farmers, HYHE farmers not only achieved a 33% increase in apple production but additionally, they increased PFP-N by 61%, reduced the N footprint by 67.6%, and increased the overall economic effect of the apple supply chain by 63.0%. This method reflects the potential for a sustainable apple supply chain and sheds light on the effective approach to improve the sustainability level of the whole supply chain.

The results summarized herein show that by improving comprehensive horticultural practices, apple growers can achieve high yields and efficient production while enhancing the sustainability of the apple supply chain. The comprehensive horticultural practices and impacts proposed in this study have potential applicability in other areas as well as in other crops for which yield efficiency needs to be improved.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/agronomy11101975/s1>, Figure S1: Distribution of basic characteristics of apple producers in Quzhou, Table S1: Formulas and parameters of N flow in apple supply chain.

Author Contributions: Conceptualization, X.J.; methodology, S.J.; software, S.J.; validation, C.Y. and X.J.; formal analysis, S.J. and Y.G.; investigation, S.J. and C.Y.; resources, X.J.; data curation, S.J. and Y.G.; writing—original draft preparation, S.J.; writing—review and editing, S.J. and X.J.; visualization,

Y.G.; supervision, X.J.; project administration, X.J.; funding acquisition, X.J. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by National Key R&D Program of China (2017YFD0200200/0200206), National Natural Science Foundation of China (NSFC) (31701999), Science and Technology Talents and Platform Program of Yunnan Province (2019IC026), and China Scholarship Council (No. 201913043).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

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

References

1. The Food and Agriculture Organization (FAO). Available online: <http://www.fao.org/faostat/en/#data/QC4> (accessed on 19 January 2018).
2. National Bureau of Statistics. *China Statistical Yearbook*; China Statistics Press: Beijing, China, 2020; pp. 387–389.
3. Wang, N.; Joost, W.; Zhang, F. Towards sustainable intensification of apple production in China—Yield gaps and nutrient use efficiency in apple farming systems. *J. Integr. Agric.* **2016**, *15*, 716–725. [\[CrossRef\]](#)
4. Zhai, H.; Shi, D.; Shu, H. Current status and developing trend of apple industry in China. *J. Fruit Sci.* **2007**, *24*, 355–360. (In Chinese with English Abstract)
5. Wang, F.; Tian, G.; Liu, J.; Ge, S.; Jiang, Y. Fate of fertilizer nitrogen and soil nitrogen pool budget of fuji apple from germination stage to new shoot growing stage. *Chin. J. Appl. Ecol.* **2019**, *29*, 931–937. (In Chinese with English Abstract)
6. Manish, S.; Sanjay, J. Agri-fresh produce supply chain management: A state-of-the-art literature review. *Int. J. Oper. Prod. Manag.* **2013**, *33*, 114–158.
7. Paam, P.; Berretta, R.; Heydar, M.; García-Flores, R. The impact of inventory management on economic and environmental sustainability in the apple industry. *Comput. Electron. Agr.* **2019**, *163*, 104848. [\[CrossRef\]](#)
8. Soto-Silva, W.; González-Araya, M.; Oliva-Fernández, M.; Plà-Aragónés, L. Optimizing fresh food logistics for processing: Application for a large Chilean apple supply chain. *Comput. Electron. Agr.* **2017**, *136*, 42–57. [\[CrossRef\]](#)
9. Khan, M.; Han, B.J. The Environmental Perspectives of Apple Fruit Supply Chain Management in Chitral, Northern Pakistan. *Int. J. Supply Chain Manag.* **2016**, *6*, 1–16.
10. Wang, J.; Li, Z.; Li, M.; Zhao, D.; Li, E.; Chen, C.; Li, Y. Based on Chinese situation, built a powerful country with Chinese characteristics in apple production. *China Fruits* **2019**, *5*, 1–6. (In Chinese with English Abstract)
11. Huang, C. Economy and Development on Shaanxi Apple Industry. Master's Thesis, Northwest A&F University, Yangling, China, 2005.
12. Sun, Y.; Hu, R.; Zhang, C. Does the adoption of complex fertilizers contribute to fertilizer overuse? Evidence from rice production in China. *J. Clean Prod.* **2019**, *219*, 677–685. (In Chinese with English Abstract) [\[CrossRef\]](#)
13. Ge, S.; Zhu, Z.; Wei, S.; Jiang, Y. Technical approach and research prospect of saving and improving efficiency of chemical fertilizers for apple in China. *Acta Hort. Sin.* **2017**, *44*, 1681–1692. (In Chinese with English Abstract)
14. Sun, Y.; Ren, B.; Wang, H.; Wang, D. Effect of organic fertilizer application on apple yield and fruit quality in North Hebei Mountainous area. *China Fruits* **2018**, *5*, 19–22. (In Chinese with English Abstract)
15. Zhang, F.; Chen, X.; Chen, Q. *The Guide to Fertilization of Major Crops in China*; China Agricultural University Press: Beijing, China, 2009; pp. 161–164.
16. Jiang, S.; Zhang, H.; Cong, W.; Liang, Z.; Ren, Q.; Wang, C.; Zhang, F.; Jiao, X. Multi-Objective Optimization of Smallholder Apple Production: Lessons from the Bohai Bay Region. *Sustainability* **2020**, *12*, 6496. [\[CrossRef\]](#)
17. Bai, X.; Wang, Y.; Huo, X.; Salim, R.; Bloch, H.; Zhang, H. Assessing fertilizer use efficiency and its determinants for apple production in China. *Ecol. Indic.* **2019**, *104*, 268–278. [\[CrossRef\]](#)
18. Ju, X.; Xing, G.; Chen, X.; Zhang, S.; Zhang, L.; Liu, X.; Cui, Z.; Yin, B.; Christie, P.; Zhu, Z.; et al. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 3041–3046. [\[CrossRef\]](#)
19. Galloway, J.N.; Townsend, A.; Erisman, J.; Bekunda, M.; Cai, Z.; Freney, J.; Martinelli, L.; Seitzinger, S.; Sutton, M. Transformation of the Nitrogen Cycle: Recent Trends, Questions, and Potential Solutions. *Science* **2008**, *320*, 889–892. [\[CrossRef\]](#)
20. Miloevi, T.; Miloevi, N. Apple fruit quality, yield and leaf macronutrients content as affected by fertilizer treatment. *J. Soil Sci. Plant Nut* **2015**, *151*, 76–83.
21. Wang, H.; Wang, L.; Wang, J.; Jiang, F.; Liu, H.; Ye, J.; Deng, N.; Xu, W.; Zhang, C.; Wang, S. Effects of vapor-permeable reflective film mulching on citrus tree micro-environment, shoot growth and fruit development. *J. Fruit Sci.* **2017**, *34*, 996–1006. (In Chinese with English Abstract)
22. Zhang, J.; Wang, C.; He, J.; Zhang, D. Effects of reflective film mulching time on apple fruit quality. *Deciduous Fruits* **2020**, *52*, 22–24. (In Chinese with English Abstract)
23. Zhou, T.; Fan, Q. Effects of organic fertilizer on growth and quality of red fuji apple. *China Soils Fert.* **2008**, *2*, 56–59. (In Chinese with English Abstract)

24. Wang, S.; Zhang, Z.; Shi, S.; Yang, S. Effect of biogas residue fertilizer on the yield and fruit quality of apple trees. *China Biogas* **2018**, *36*, 74–79. (In Chinese with English Abstract)
25. Gong, M.; Wang, H.; Zhang, X.; Liu, Y.; Li, H.; Guo, S. Effects of different organic fertilizer amounts on soil nutrient and enzyme activity of apple orchard. *J. Northwest For. Univ.* **2019**, *34*, 74–78. (In Chinese with English Abstract)
26. Chen, Q.; Ding, N.; Peng, L.; Zhu, Z.; Ge, S. Nitrogen application technology in dwarfed apple trees. *J. Appl. Ecol.* **2018**, *29*, 1429–1436. (In Chinese with English Abstract)
27. Kumar, P.; Suman, S.; Spehia, R.; Kumar, V.; Kaith, N. Studies on method and rate of fertilizer application in apple under mulch in north-western Himalayas. *J. Plant Nutr.* **2016**, *39*, 219–226. [[CrossRef](#)]
28. Alkaabneh, F.; Lee, J.; MI, G.; Gao, H. A systems approach to carbon policy for fruit supply chains: Carbon tax, technology innovation, or land sparing? *Sci. Total Environ.* **2020**, *767*, 144211. [[CrossRef](#)]
29. Cai, Y.; Qiao, Y.; Xu, J.; Meng, F.; Wu, W. Environmental impact assessment via life cycle analysis for organic and conventional apple productions. *Chin. J. Eco-Agric.* **2017**, *25*, 1527–1534. (In Chinese with English Abstract)
30. Longo, S.; Mistretta, M.; Guarino, F.; Cellura, M. Life Cycle Assessment of organic and conventional apple supply chains in the north of Italy. *J. Clean Prod.* **2017**, *140*, 654–663. [[CrossRef](#)]
31. Parajuli, R.; Thoma, G.; Matlock, M. Environmental sustainability of fruit and vegetable production supply chains in the face of climate change: A review. *Sci. Total Environ.* **2019**, *650*, 2863–2879. [[CrossRef](#)]