Life Cycle Assessment of Environmental Impacts of Organic and Conventional Apple Production: Postprint

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Abstract

This study investigates apple production, a crucial fruit crop in China' s horticultural industry, focusing on the environmental impacts of organic and conventional cultivation in three representative regions—Fushan (Shanxi), Baishui (Shaanxi), and Tianshui (Gansu)—through field research and life cycle assessment methodology, aiming to provide scientific evidence for sustainable agricultural development and ecological civilization construction in China. The results indicate that organic apple production in Fushan, Shanxi exhibits higher nutrient use efficiency compared to conventional production, whereas the opposite pattern occurs in Baishui, Shaanxi and Tianshui, Gansu. Across all three regions, energy consumption per unit of apple under organic production constitutes less than 26% of that under conventional methods, with organic production demonstrating superior energy use efficiency. Among the four environmental impact categories—energy consumption, global warming, environmental acidification, and eutrophication—eutrophication represents the dominant contribution, accounting for over 80% of total impacts. The environmental impacts of both organic and conventional apple production follow a consistent regional hierarchy: Baishui, Shaanxi > Tianshui, Gansu > Fushan, Shanxi. In Fushan, Shanxi, substantially lower fertilizer inputs in organic apple production, coupled with comparable yields, result in a comprehensive environmental impact of organic apples equivalent to merely 22% of conventional production. Conversely, Baishui, Shaanxi and Tianshui, Gansu exhibit the reverse scenario, with comprehensive environmental impacts of organic apples reaching 356% and 138% of conventional production, respectively. Under conditions of high organic nutrient input, organic agriculture can achieve yields comparable to conventional agriculture, but this comes at the cost of elevated negative environmental impacts and reduced nutrient and energy use efficiencies.

Full Text

Preamble

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Environmental Impact Assessment via Life Cycle Analysis for Organic and Conventional Apple Productions

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Abstract: This study investigated the environmental impacts of organic and conventional apple production in three representative regions of China—Fushan (Shanxi Province), Baishui (Shaanxi Province), and Tianshui (Gansu Province)—using life cycle assessment (LCA) methodology based on field surveys. The aim was to provide scientific evidence for sustainable agricultural development and ecological civilization construction in China. Results showed that nutrient use efficiency in organic apple production was higher than conventional production in Fushan, Shanxi, but lower in Baishui, Shaanxi and Tianshui, Gansu. Energy consumption per unit of organic apples in all three regions accounted for less than 26% of conventional production, indicating higher energy use efficiency in organic systems. Among four environmental impact categories—energy consumption, global warming, environmental acidification, and eutrophication—eutrophication contributed the most (>80%) to total environmental impact. The overall environmental impact ranking for both production systems was Baishui > Tianshui > Fushan. Due to substantially lower fertilizer inputs and comparable yields, organic apples in Fushan exhibited only 22% of the environmental impact of conventional apples. Conversely, organic apples in Baishui and Tianshui showed 356% and 138% of the environmental impacts of their conventional counterparts, respectively. While high organic nutrient inputs can achieve yields comparable to conventional agriculture, this comes at the cost of greater negative environmental impacts and lower nutrient and energy use efficiencies.

Keywords: Organic agriculture; Apple; Life cycle assessment; Environmental impact; Nutrient use efficiency; Energy use efficiency; Eutrophication

Introduction

Agricultural production systems generate widespread environmental impacts, including climate change, acidification, and eutrophication. These impacts vary considerably across regions due to differences in natural conditions and management practices, as well as across production methods and products. An increasing number of studies have analyzed the comprehensive environmental impacts of different agricultural products and production systems, with life cycle assessment (LCA) emerging as a widely adopted methodology that evaluates environmental impacts across all factors involved in production systems [1]. In 1996, the International Organization for Standardization released ISO 14040 (principles and framework), followed by ISO 14042 (impact assessment) in 2000 [2], establishing distinct analytical frameworks and methods for industrial and agricultural sectors [3-4] that provide methodological support for LCA applications in agriculture.

The environmental impacts of crop production extend beyond agricultural activities themselves to include those from agricultural inputs, such as pollutant emissions and resource consumption during fertilizer manufacturing [5]. Consequently, LCA methodology has been increasingly applied to agricultural production systems, including environmental impact assessments of organic versus conventional agriculture. Chinese scholars have conducted numerous studies using LCA, evaluating environmental impacts for greenhouse vegetables [6], winter wheat (*Triticum aestivum*) in the North China Plain [7], and banana (*Musa nana*) cultivation [8].

Organic and conventional agriculture exhibit different environmental benefits due to variations in production processes and inputs. For instance, Meng et al. [9] quantitatively demonstrated that Chinese organic agriculture provides superior environmental benefits in reducing nitrate pollution, carbon sequestration, and biodiversity improvement, with values that could compensate for a substantial portion of economic losses from yield reductions. Luo et al. [10] applied LCA to show that organic soybeans (*Glycine max*) had a lower comprehensive environmental impact index than conventional soybeans, with resource consumption, acidification, and global warming accounting for approximately 30% of the total environmental impact, while contributions from eutrophication and ecotoxicity were relatively low. Li et al. [11] conducted a life cycle assessment of organic and conventional strawberry (*Fragaria ananassa*) production, finding that organic strawberry production had smaller environmental impacts, primarily due to lower impacts from organic fertilizers and bio-pesticides used in the production process.

Beyond production processes and inputs, the environmental impacts of agricultural products in different regions are also influenced by natural conditions and management practices. For example, Li et al. [12] found that eutrophication was the most significant environmental impact, with considerable variation among farmers, and that Jilin Province had advantages in lower resource and environmental impacts due to its natural conditions. In LCA analysis, environmental impacts can be expressed per unit area or per unit crop yield, which carry completely different economic and social implications. To date, most studies have focused on environmental impact analysis of organic or conventional products in a single region, with relatively few comparative studies examining organic and conventional products across different regions. Therefore, this paper selected apple (*Malus domestica*), an important horticultural crop in China, to analyze its environmental impacts across different regions and production methods, aiming to provide scientific evidence for sustainable agricultural development and ecological civilization construction in China.

1.1 Study Objects and Data Sources

The study areas were Fushan (Shanxi Province), Baishui (Shaanxi Province), and Tianshui (Gansu Province), with organic and conventional apple production systems selected in each region. Organic production refers to agricultural practices that follow specific principles: no use of genetically engineered organisms or their products, no application of chemically synthesized pesticides, fertilizers, growth regulators, or feed additives; adherence to natural laws and ecological principles; balancing crop cultivation and livestock husbandry; and adoption of sustainable agricultural technologies to maintain stable agricultural production systems [13]. Relevant data on apple production were obtained through field surveys of local organic producers and nearby conventional enterprises.

The survey sites included: Zhongbao Agricultural Development Co., Ltd. in Fushan County, Fushan City, Shanxi Province, with 29.95 ha of certified organic apple orchards; Hongda Fruit Industry Co., Ltd. in Baishui County, Shaanxi Province, with 533.3 ha of organic apple orchards; and Longnan Great Wall Juice Beverage Co., Ltd. in Tianshui, Gansu Province, with 400 ha of organic apple orchards. Similar areas of conventional apple production were surveyed in each region. Climatic and soil conditions were: Fushan, Shanxi—mean annual temperature 11.2°C, annual precipitation 532.7 mm, cinnamon soil; Baishui, Shaanxi—mean annual temperature 11.4°C, annual precipitation 577.8 mm, cinnamon soil; Tianshui, Gansu—mean annual temperature 11.0°C, annual precipitation 491.7 mm, loess soil.

1.2.1 Goal Definition and Scope

The functional unit is the basis for environmental impact comparison in LCA, requiring clear definition of study objectives and relevant functional units [14]. This study used the production of 1 tonne of apples as the functional unit to evaluate organic and conventional apple production in the three regions. System boundaries spanned from agricultural input production to the cropping stage, terminating at agricultural product output and pollutant emissions (Figure 1 [Figure 1: see original paper]). The study considered four environmental impact categories: energy consumption (RU), global warming potential (GWP), environmental acidification potential (AP), and eutrophication potential (EP).

1.2.2 Inventory Analysis

Inventory analysis is the core component of LCA, quantifying all resource inputs and material outputs related to the functional unit within system boundaries.

The focus was on agricultural production processes and their environmental impacts. Given the complexity of agricultural systems with numerous subsystems, independent analysis of subsystems is more practical [15]. Since pesticide use is minimal in conventional apple production and China lacks life cycle inventory data for pesticides, pesticide emissions and toxicity were not included in this study.

The calculation method involved characterization, standardization, and weighting. Characterization converts different impact indicators within the same category into uniform units. This study employed the equivalency factor method, which utilizes differences in contributions of various environmental stressors to the same impact type. One stressor is selected as the reference with an impact potential of 1, and other pollutants are compared against it to derive relative equivalency coefficients. This approach, based on scientific research, assumes that the same stressor produces identical potential environmental impacts regardless of exposure pathways or locations, making results independent of temporal and geographic factors [16].

The study examined four impact categories: GWP, RU, AP, and EP. GWP used CO as the reference (CO -equivalent), with equivalency factors of 21 for CH and 310 for N O [17]. AP used SO as the reference, with factors of 1.88 for NH and 0.7 for NO . EP used PO ^{3} as the reference, with factors of 0.13 for NH , 0.42 for NO , and 0.33 for NO [18].

Standardization establishes benchmarks to enable relative comparability across impact types. Different environmental impacts have varying relative importance for sustainable resource use, ecosystems, and human health, necessitating weighting. Reference values and weighting coefficients are shown in Table 1 , based on 2000 global per capita values. Standardization was calculated by dividing characterization results by reference values [19], with weighting following Ji et al. [20].

Survey data revealed that organic apples in Fushan, Shanxi were primarily for export, with relatively low organic fertilizer application (5,250 kg • hm ^{2}) to preserve flavor. Conventional production applied 12,750 kg • hm ^{2} organic fertilizer plus 3,375 kg • hm ^{2} compound fertilizer, with organic fertilizer containing 1.92% N, 0.61% P O , and 1.13% K O, and compound fertilizer containing 15% each of N, P O , and K O. In Baishui, Shaanxi, organic apples used 180 t • hm ^{2} organic fertilizer, while conventional production used 4,500 kg • hm ^{2} compound fertilizer, with organic fertilizer containing 0.85% N, 0.27% P O , and 0.73% K O. In Tianshui, Gansu, organic production applied 45 t • hm ^{2} organic fertilizer containing 2.17% N, 0.70% P O , and 1.95% K O, while conventional production used 450 kg • hm ^{2} compound fertilizer plus 45 t • hm ^{2} organic fertilizer containing 1.38% N, 0.32% P O , and 1.42% K O, with compound fertilizer containing 15% each of N, P O , and K O.

Following Ji et al. [20], pollutant emissions from organic agricultural inputs primarily originated from CH , NO , and NH during composting (0.648 g •

kg ^{1}, 0.045 g · kg ^{1}, and 0.961 g · kg ^{1}, respectively), with energy consumption mainly from manure collection, processing, and transport (11.43 GJ per tonne of pure N). Conventional agricultural emissions came from chemical fertilizer manufacturing, using data from Liang et al. [18] (Table 2).

For calculating energy consumption and pollutant emissions from cropping systems, this study referenced emission coefficients of 0.0219 kg · kg ^{1} for apparent nitrogen leaching, 0.112 kg · kg ^{1} for NH volatilization, and 0.010 kg · kg ^{1} for N O loss [21-22].

2.1 Fertilizer Nutrient Input and Energy Consumption Analysis

Based on survey data, fertilizer inputs for organic and conventional apple production were calculated (Table 3). Organic apple yield in Fushan, Shanxi was 69% of conventional yield, while yields in Baishui, Shaanxi and Tianshui, Gansu were comparable or slightly higher under organic management. Nutrient input per unit yield (the inverse of nutrient use efficiency) in Fushan' s organic production was far lower than conventional, whereas the other two regions showed higher organic inputs (except P in Baishui), indicating higher nutrient use efficiency in Fushan' s organic system but lower efficiency in Baishui and Tianshui. Across all three regions, nutrient use efficiency followed the pattern Fushan > Tianshui > Baishui for both production systems (except P in Tianshui where conventional efficiency was highest).

Energy consumption per unit product (the inverse of energy use efficiency) was higher in conventional production across all three regions: organic consumption was 18% of conventional in Fushan, 26% in Baishui, and 14% in Tianshui, demonstrating higher energy use efficiency in organic systems. This difference stems from substantially higher energy requirements for chemical fertilizer manufacturing compared to composting, with fertilizer energy dominating total consumption. In organic systems, energy consumption per unit product followed the pattern Gansu Tianshui < Shanxi Fushan < Shaanxi Baishui, corresponding to energy use efficiency of Tianshui > Fushan > Baishui. This ranking reflects much higher labor and irrigation energy consumption in Baishui and Fushan compared to Tianshui. In conventional systems, energy use efficiency ranked as Fushan > Tianshui > Baishui, with chemical fertilizer use following Baishui > Tianshui > Fushan, and fertilizer production accounting for over 90% of energy consumption (except in Baishui where both fertilizer and irrigation energy were highest).

2.2 Environmental Impact Assessment Inventory

The life cycle environmental impact inventory for organic and conventional apples is presented in Table 4 . Energy consumption per unit product from input systems was far lower in organic systems across all regions. In cropping systems, however, organic energy consumption was lower than conventional only in Baishui, while Fushan and Tianshui showed the opposite pattern. In conventional production, energy consumption was concentrated in input systems, accounting for 98.1% in Fushan, 69.9% in Baishui, and 99.2% in Tianshui. Organic production showed different patterns: input systems accounted for only 11.0% in Fushan, 55.5% in Baishui, and 89.5% in Tianshui.

From a global warming perspective, only Fushan' s organic production had lower impact than conventional (23% of conventional), while Baishui and Tianshui showed higher organic impacts–3.37 and 1.42 times conventional, respectively. Overall global warming impact ranked Baishui > Tianshui > Fushan for both systems, though differences were less pronounced under conventional management. Greenhouse gas emissions originated primarily from cropping systems, with organic lower than conventional in Fushan but higher in Baishui and Tianshui; input systems consistently showed higher organic emissions.

Environmental acidification per unit product followed the pattern Baishui > Tianshui > Fushan for both systems, with similar regional differences under conventional management. Only Fushan showed conventional impacts exceeding organic in both input and cropping systems, while Baishui and Tianshui exhibited higher acidification under organic management. Acidification was concentrated in cropping systems (except for organic management in Baishui).

Eutrophication per unit product was highest in Baishui, followed by Tianshui, then Fushan, with both systems showing greater impacts from cropping systems. In Fushan, conventional eutrophication exceeded organic (organic was 22% of conventional), while Baishui and Tianshui showed higher impacts under organic management in both systems.

2.3 Comprehensive Environmental Impact Analysis

After standardization and weighting, environmental impacts per unit product are shown in Table 5 . Organic production in Fushan had lower environmental impact than conventional, while Baishui and Tianshui showed organic > conventional. Overall, both production systems ranked Baishui highest, followed by Tianshui, then Fushan. This pattern resulted from lower fertilizer and energy inputs in Fushan' s organic system compared to conventional, leading to lower pollutant emissions and energy consumption. Across all three regions, environmental impacts were dominated by eutrophication (>81%), consistent with high fertilizer inputs and nitrogen leaching and volatilization from cropping systems.

Organic apple production in Fushan had only 22% of the environmental impact of conventional production, while Baishui and Tianshui showed 356% and 138%, respectively. This discrepancy primarily reflects differences in fertilizer type and quantity. The results demonstrate that while high organic nutrient inputs can achieve yields comparable to conventional agriculture, this comes at the cost of higher negative environmental impacts and lower nutrient and energy use efficiencies.

Organic agriculture, centered on sustainable development, aims to reduce chemical and external resource inputs, utilize local and biological technologies, achieve nutrient cycling and efficient energy use, and minimize chemical and non-renewable energy consumption. Its ecological and environmental protection functions are particularly valuable from a long-term, holistic perspective [23-24]. Comparative environmental impacts of conventional and organic agriculture can be categorized as: 1) reduced pesticide/veterinary drug use, 2) reduced chemical fertilizer use, 3) carbon sequestration and emission reduction, 4) increased agricultural biodiversity, 5) reduced nitrogen leaching and groundwater pollution, 6) improved energy use efficiency, and 7) reduced yields [25-29].

In this study, two regions (Baishui and Tianshui) achieved comparable yields between organic and conventional systems, while Fushan' s organic yield was 69% of conventional. This difference primarily stemmed from fertilizer inputs: Fushan's organic N, P, and K inputs were only 6.8%-18.8% of conventional levels, while the other two regions' organic inputs were 72.7%-228.8% of conventional, confirming that high organic nutrient inputs can match conventional yields, as validated in other studies [28].

Although both systems can achieve comparable yields under high-input conditions, nutrient use efficiency, energy use efficiency, and environmental impacts differ substantially [30]. Fushan' s low organic fertilizer inputs resulted in higher nutrient use efficiency compared to conventional, while the other regions showed lower organic efficiency. Across all regions, nutrient use efficiency ranked Fushan > Tianshui > Baishui for both systems, directly related to local fertilization practices—Baishui farmers prioritize high fertilizer inputs to ensure high, stable yields.

Energy use efficiency was higher in all organic systems due to lower energy consumption than conventional production. Among conventional systems, efficiency ranked Fushan > Tianshui > Baishui, reflecting Baishui' s highest chemical fertilizer use with minimal yield differences. Among organic systems, efficiency ranked Tianshui > Fushan > Baishui, as Baishui and Fushan had much higher labor and irrigation energy consumption than Tianshui.

This study analyzed apple production environmental impacts across four categories: energy consumption, global warming, environmental acidification, and eutrophication. Due to Fushan' s substantially lower fertilizer inputs and comparable yields, organic apples had only 22% of conventional apples' environmental impact, while Baishui and Tianshui showed the opposite pattern (355% and 138%, respectively). These findings differ from Li et al. [11], primarily because their study had lower organic yields. Regional comparisons showed consistent ranking: Baishui > Tianshui > Fushan for both systems. Eutrophication dominated total impacts (81%-83%), followed by acidification (15%-17%), consistent with findings for winter wheat [7] and vegetables [31]. This indicates that Chinese agriculture has entered a highly intensive stage, with current development priorities focusing on reducing chemical fertilizer and pesticide inputs.

Furthermore, organic fertilizer production and application generate significant environmental impacts, including NH volatilization and greenhouse gas (N O, CH) emissions during composting and after soil application [32]. In some cases, such as Baishui and Tianshui, these impacts exceed those of conventional production. Therefore, as China promotes agricultural model transformation, organic agriculture' s environmental impacts warrant careful consideration. Moreover, most nitrogen in current Chinese organic production ultimately originates from chemical industry sources rather than natural nitrogen fixation by legumes [33]. Consequently, organic agriculture promotion should proceed judiciously rather than rashly.

This study provides a comprehensive evaluation of organic and conventional apple production and their primary environmental impacts from a whole-process perspective. The key determinants of yield, nutrient use efficiency, energy use efficiency, and comprehensive environmental impact are organic and chemical fertilizer input levels. While high organic nutrient inputs can match conventional yields, this entails higher negative environmental impacts and lower resource use efficiencies. Both production systems in all three regions face challenges in improving nutrient and energy use efficiency.

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