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RESEARCH ARTICLE

Life cycle assessment of potential environmental burden and human capital loss caused by apple production system in China

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Abstract

As one of the representative fruits of China, apple plays an important role in the overall agricultural production system. However, the large amount of chemical inputs in apple production has potential detrimental impacts on the environment and human health, and thus threatens the achievement of sustainable development goals. Therefore, a comprehensive evaluation of the environmental burden (EB) and human capital (refer to human lives) loss (HCL) caused by apple production system (APS) is urgently needed to suggest directions for improvement. A method widely used to measure impacts from both the use of resources and the emissions generated in the agriculture sector is the life cycle assessment (LCA). In this study, the EB and HCL caused by the APS have been determined from two phases using the LCA methodology in China. The results show that the leading cause of EB in the agricultural materials' production phase is nitrogen fertilizer (N) production, and in the farming phase is chemical fertilizer use. The top 5 major pollutants that cause potential damage to human health in APS are carbon dioxide (CO_2), ammonia (NH_3), nitrogen dioxide (N_2O), nitrate (NO_3), and sulfur oxides (SO_x). The human health risk (HHR) is 5.84×10^{-2} disability-adjusted life year to cultivate 1 ha of the apple orchard 1 year, and the corresponding HCL is about 4230 Chinese yuan (CNY). Under the scenario analysis of a 15% reduction in chemical fertilizer use and a 20% increase in organic fertilizer (mainly dried sheep dung) use, most of the environmental impact categories have a decreasing trend, and the HCL decreased by 438 CNY of 10.36%. Therefore, chemical fertilizer (especially N) is the most critical environmental hotspot in APS, and our results suggest that the replacement of chemical fertilizers by organic fertilizers is an effective solution to reduce the potential EB and HCL and improve the sustainability of the APS.

Keywords Apple production · Environmental impact · Human capital loss · Life cycle assessment · China

Abbreviations

AC	Acidification
AD	Abiotic depletion
AD (FF)	Abiotic depletion fossil fuels
APS	Apple production system
As	Arsenic
BOD	Biochemical oxygen demand
Cd	Cadmium
CH_4	Methane
CNY	Chinese yuan
CO	Carbon monoxide
CO_2	Carbon dioxide
COD	Chemical oxygen demand
Cr	Chromium
Cu	Copper
DALY	Disability-adjusted life year
EB	Environmental burden
EU	Eutrophication
FAE	Freshwater aquatic ecotoxicity
FU	Functional unit
GW	Global warming
HC	Hydrogen carbonate
HCL	Human capital (refer to human lives) loss
Hg	Mercury
HHR	Human health risk
HT	Human toxicity

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K_2O	Potassium fertilizer
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life Cycle impact assessment
MAE	Marine aquatic ecotoxicity
N	Nitrogen fertilizer
N_2O	Nitrogen dioxide
NH_3	Ammonia
NH_4	Ammonium nitrate
NO_3	Nitrate
NO_x	Nitrogen oxide
OLD	Ozone layer depletion
Pb	Lead
PM_{10}	Inhalable particle matter
P_2O_5	Phosphate fertilizer
PO	Photochemical oxidation
P_{tot}	Total phosphate
SO_x	Sulfur oxides
TE	Terrestrial ecotoxicity
Zn	Zinc

Introduction

Agriculture is related to food security and ecological environment, human health, social development, cultural heritage, and animal welfare protection (Yu et al. 2021). However, the environmental problems can be caused by a large number of agrochemicals in agriculture production. In recent years, environmental issues such as resources waste, soil and water pollution, air quality declining, and non-point source pollution in the agricultural sector have attracted increasing attention worldwide (Lassaletta et al. 2014; Cordes et al. 2016; Huang and Yang 2017; Goossens et al. 2017; Shen et al. 2021), and most countries are committed to exploring effective paths to achieve sustainable development of agricultural production systems. In China, a country with a large population, it is common to rely heavily on agrochemicals such as fertilizers and pesticides in order to increase the yield of agricultural products (Sun et al. 2019a, b). However, this higher-tension input mode to agricultural production can lead to more prevalent detrimental impacts on the environment, ecosystem, food safety, and even human health (Liang et al. 2019; Wang and Zhao 2019). Specifically, the way it is affected is mainly through the following four aspects: First, excessive fertilizers and pesticides often cause excessive accumulation of certain elements in the soil and changes in the physical and chemical properties of the soil, then causing land pollution, which is not conducive to the growth of crops in the long run and may also greatly reduce the quality of agricultural products. Second, excessive fertilizers and pesticides can cause large areas of water sources' pollution because the ecosystem is cyclical, which in turn leads to a detrimental impact on aquatic organisms (such as fish and shrimp). Third, excessive fertilizers and pesticides through evaporation and transpiration into the air spread with the wind, causing atmospheric pollution. Fourth, soil, water, and air pollution caused by excessive fertilizers and pesticides can have not only a direct impact on human health, but also indirectly through the consumption of food containing pollutants (especially cadmium, arsenic, and lead, which are carcinogenic heavy metals) on human health, and finally lead to increased human health risk (HHR).

It is noteworthy that fruits and vegetables are important options for farmers in China to improve their household income due to the higher comparative returns (Li et al. 2021; Huang 2022). However, compared to grain production, farmers invest a more significant amount of chemical fertilizers and pesticides in cultivating fruits and vegetables (Zhang et al. 2017; Li et al. 2018). Despite many national policies related to fertilizer and pesticide reduction in recent years, the average fertilizer use per acre for fruit trees in China is still more than twice that of Japan, six times that of the USA, and seven times that of the European Union; the pesticide use is also much higher than international levels, so the amounts of them are considered excessive (Su and Li 2020; Cheng et al. 2022b), which driven mainly by farmers' own profit-seeking nature and the misconception of high input-high output (Li et al. 2018), thus leading to environmental pollution, ecosystem damage, and human capital (refer to human lives) loss (HCL) (Zhu et al. 2018; Wang and Zhao 2019). This situation is not only contrary to the development pattern of China's agricultural modernization but also not conducive to the realization of sustainable development goals. No. 1 Central Documents have repeatedly emphasized that ecological and environmental protection issues should be addressed strategically and that agricultural production must adhere to a green and sustainable development path (CPC Central Committee and State Council 2021, 2022), so it is important to look for the main obstacles facing the production process of key agricultural products.

Apples are one of the most commonly consumed fruits and also one of the most popular fruits in the world, since rich in minerals and vitamins. China is the world's largest producer of apples, with 2.08 million hectares of planted area and 41 million tons of production in 2020, which were all more than 50% of the world's total; China is the largest exporter of fresh apples as well; it exported 1.06 million tons of fresh apples in 2020, mainly to Bangladesh, Philippines, Vietnam, Thailand, Indonesia, and other neighboring countries. Moreover, it is also the largest exporter of concentrated apple juice, mainly exported to the USA, South Africa, Russia, Japan, Turkey, and other countries and regions with export volume of 455,300 tons in 2020, and the study of Cheng et al. (2022a) suggests that 6.5 tons of fresh apples are needed to produce 1 ton of concentrated apple juice. Shaanxi Province is the largest producer of apples in China, with 645,800 hectares of planted area produced 11,852,100 tons of apples in 2020, accounting for the share of 31% and 29% in China, respectively, which means apple production plays a vital role in the agricultural production system in this province (Zhu et al. 2018). However, studies on the environmental and human health impacts of apple production in China are relatively rare. It is necessary to complement the relevant studies on China, and this study attempts to do this. We believe it is beneficial to guide the sustainable development of Chinese apple production on the one hand and build a bridge between the world and China for comparative studies on the other, thus having significant potential practical guidance. So there is an urgent need to develop appropriate methods to assess the detrimental impacts of the apple production system (APS) in depth.

The technique of life cycle assessment (LCA) can provide a collection of systematic methods to gather and evaluate potential impacts to environment and human health resulting from extractions or emissions into the environment across a product's life cycle (ISO 14044, 2006), which thus become an important tool to support sustainable development plans. There are a growing number of studies which explore apple production in China and globally in recent decades using the LCA methodology (Alaphilippe et al. 2016; Longo et al. 2017; Zhu et al. 2018; Vinyes et al. 2017; Bartzas et al. 2017; Svanes and Johnsen 2019). More specifically, some studies have conducted the comparative environmental evaluation of different cultivars (Milà i Canals et al. 2006; Cerutti et al. 2013), different production systems such as conventional versus organic farms, intensive versus semi-extensive apple orchards (Keyes et al. 2015; Alaphilippe et al. 2016; Longo et al. 2017; Zhu et al. 2018), and even domestic versus imported apple origins (Milà i Canals et al. 2007); and some studies have compared the environmental impacts of apple and other crop production such as peach, pistachio, almond, sweet cherry, and plum (Vinyes et al. 2017; Bartzas et al. 2017; Svanes and Johnsen 2019). The results of the above-mentioned study showed that apple production can lead to some impacts on the environment such as global warming, acidification, aquatic eutrophication, soil eco-toxicity, and human toxicity. However, the environmental burden (EB) of the same production system varies considerably under different management practices and strategies, mainly due to different chemical input structures and different resource consumption under different operation modes. In comparison, advanced management practices can significantly reduce detrimental environmental impacts (Goossens et al. 2017). Besides, an interesting finding of the existing studies on LCA of APS is that most researchers mainly focused only on the detrimental environmental impacts, and no consideration of the impact on human health.

Along with the need to solve real-life problems, the updated methods were born. The methodology ReCiPe 2016 usually used to convert various environmental pollutants in each production phases of life cycle into a limited number of impact scores for the midpoint and endpoint levels (Huijbregts et al. 2017). Some researchers have used the ReCiPe 2016 method to analyze the impact of agricultural production processes on human health (Mahmud et al. 2019; Wang and Zhao 2019; Wang and Lu 2020); they measured endpoint indicators of potential damage to human health using disability-adjusted life year (DALY), which values for diseases are derived from life year loss or related disability in human health statistics. Some studies showed that agricultural emissions bring the most considerable relative contribution to fine particulate matter; and fine particulate matter has a significant detrimental impact on human health under long-term exposure, which can lead to respiratory and cardiovascular diseases, lung disease, and other health problems (Lelieveld et al. 2015; Thurston et al. 2016; Stieb et al. 2016; Gao et al. 2018). Wang and Zhao (2019) explored the issue of HCL due to potential pollutants in maize, vegetable, and peach production systems in Beijing of China, and their findings showed that HCL in different production systems was closely related to the amount and type of agrochemicals. However, these studies have focused on the effects of agricultural production systems on human health, but have neglected the effects on the environment.

Overall, there is room for improvement the gaps in knowledge of focusing on the relationship among production processes, EB, and HCL in the agricultural production systems comprehensively. Since agriculture production systems usually have some impact on the environment and also direct or indirect effects on human health, they need to be studied systematically using a combination of different research methods. However, few studies have used different approaches of LCA simultaneously to analyze the different impacts of agricultural production systems in a multidimensional way. Besides, there have been few studies to focus both on EB and HCL in APS, and evaluate the impacts caused by all kind of pollutants in the production system using LCA method. So the relationship among environmental impact, human health impact, and apple production processes remains poorly understood. Thus, it is important to find the method that can be used to evaluate pollutant-induced EB and HCL caused by the APS, which directly related to the green and sustainable development of the apple industry in China.

The aim of this study is to determine, for the first time, the EB and HCL caused by the APS in China, then to explore the feasible mitigation options. To do so, we select Baishui County in Shaanxi Province, a typical area of apple production in China, as the study area; consider the system boundary from the agricultural materials production to farming phase; and use the CML-IA baseline and ReCiPe 2016 methods simultaneously of the LCA. Accordingly, targeted improvement strategies are proposed to provide some reference basis for apple farmers and policy-makers in China.

Materials and methods

Study area and data sources

Study area

Our study area is Baishui County, which is located in the northeast region of Shaanxi Province in China, its ranges from approximately 109°16′–109°45′E and 35°4′–35°27′ N. The county covers a total area of 986.6 km^2 and has 48,000 ha of arable land, which is well-suited for apple cultivation due to its natural geographic and climatic advantages. The average elevation of the county is 850 m. Besides, the county has a warm temperate continental monsoon climate, with great variation in weather conditions throughout the year. Specifically, the county's climate is characterized by rapid warming and dryness in the spring, with more cold air activity; high temperatures and humidity in the summer, with more rain showers and precipitation; rapid cooling in the fall, with rain and humidity; and cold, dry, and windy in the winter. In terms of overall average conditions, the average annual solar radiation is 128.13 kcal/cm·year, the average annual sunshine duration is 2252 h, the average annual temperature is 11.4 °C, and the average annual precipitation is 577.8 mm (citation source: http://www.baishui.gov.cn/). Studies have shown that apples prefer a cool and dry climate with sufficient sunlight and a large temperature difference between day and night (Zhu 2019; Fan 2021). Specifically, the suitable conditions for growth are an altitude of 800 to 1200 m, an average annual sunshine duration of 1100 to 2400 h, an average annual temperature of 7 to 15 °C, and an annual precipitation of 500 to 800 mm. Obviously, all of these optimal production conditions are met in Baishui County.

Moreover, Baishui County has become the largest organic apple production base in China and being globally recognized as the best apple-growing region in the world (Lu et al. 2022). The apples produced in this area are thin-skinned, juicy, moderate sweetness and acidity, crispy, and delicious, so are well known throughout the country and favored by consumers, even world-renowned. In 2020, there were 36,700 ha of land used for apple cultivation in Baishui County, with a total yield of 530,000 tons of apples, which corresponds to 14.44 tons/ha; it was lower 26.44% than the national level in China (19.63 tons/ha), since the yields in Baishui County were affected by hail and drought in the year. Overall, the apple production of Baishui County is representative of the national average situation, with the planted area of 5.68% and 1.76% in Shaanxi Province and China, respectively. The share of planted area in Baishui County is more than average value of the main apple-producing counties in China; even more importantly, most apple farms in Baishui County are 0.7 ± 0.2 ha, and owned by smallholders, a scale of apple production that is also typical of the country (Fan 2021).

Data sources

The data used in this study are obtained from foreground and background data systems. The foreground data set includes all data associated with the apple production, which came from the research on apple farmers in Baishui County, Shaanxi Province, in October 2020. A random sampling method was used to select five townships in Baishui County, about 30 apple farmers were chosen in each township for a face-to-face interview survey on the production and operation of apple orchards in 2020. A total of 147 questionnaires were obtained, and 8 with incomplete critical information were excluded, leaving 139 valid questionnaires for use in this study, of which containing the information of 237 apple farms with different ages distributed from 1 to 40. And the questionnaire obtains essential details on the consumption information of input resources required for different operation steps, such as fertilizer, pesticide, diesel for agricultural machinery and equipment, irrigation water, human labor, and apple output in the apple production phase. While the background data set comprises the production information of consumable inputs (e.g., fertilizer, pesticide, diesel), the information obtained mainly through Ecoinvent 3 and Industry data 2.0, which are actual databases in the SimaPro software system. The relevant background data are listed in Table S1.

Table 1 shows the inputs for 1 ha of the apple orchard in 2020 in Baishui County, Shaanxi Province, and compiles from research data provided by 139 farmers, and the weighted average value of 237 apple farms. It should be noted that each farm containing trees with different ages distribute from 1 to 40, which means that the inputs are different for different trees. To simplify the analysis, we have divided the main production cycle of apples into four stages including the unfruitful stage (1–3 years), the early production stage (4–6 years) of little fruit harvested, the main producing stage (7–35 years), and the decline stage of low yield in orchards (36–40 years), and calculated the weighted average value according to the proportion of trees at different production stages.

The inputs of nitrogen fertilizer (N), phosphate fertilizer (P_2O_5), and potassium fertilizer (K_2O) were 804, 694, and 674 kg/ha, respectively, of which the share of chemical fertilizers was 88.18, 93.08, and 85.91%, respectively. Referring to the study of Zhu et al. (2019), it was learned that the

Table 1 Apple production inputs in Baishui County of Shaanxi Province in 2020

Inputs	Unit	Category	1 ha
N	kg		8.04×10^2
		From chemical fertilizers	7.09×10^2
		From organic fertilizers	9.55×10^1
P_2O_5	kg		6.94×10^2
		From chemical fertilizers	6.46×10^2
		From organic fertilizers	4.78×10^1
K_2O	kg		6.74×10^2
		From chemical fertilizers	5.79×10^2
		From organic fertilizers	9.55×10^1
Pesticide (a.i.)	kg		1.43×10^1
		From fungicides	1.01×10^1
		From insecticides	1.84
		From herbicides	1.47
Diesel	kg		5.34×10^2
Irrigation water	L		5.45×10^5
Human labor	h		9.36×10^3

Data from the survey of 139 apple farmers in Baishui County and own calculated the weighted average of 237 apple farms. *N* nitrogen fertilizer, *P_2O_5* phosphate fertilizer, *K_2O* potassium fertilizer, *a.i.* active ingredient

national average N, P_2O_5, and K_2O inputs for apple cultivation were 1056.12, 687.34, and 861.12 kg/ha, respectively, of which the share of chemical fertilizers was 81.20, 79.11, and 81.65%, respectively. Apparently, the inputs of N and K_2O in apple production in Baishui County, Shaanxi Province, were both lower than the national level and the input of P_2O_5 was slightly higher than the national level. However, the percentage of chemical fertilizer used in apple production in Baishui County was higher than the national average, which means that the share of organic fertilizer used was lower.

The types and amounts of fertilizers used for apple farmers vary depending on the planting situation. According to the field research, we found that the types of fertilizer commonly used in the study area include compound fertilizers, water-soluble fertilizers, and organic fertilizers. Since N, P_2O_5, and K_2O are common active ingredients in various fertilizers, all fertilizers are converted into amounts of N, P_2O_5, and K_2O to accurately estimate emissions associated with fertilizer application based on Xue et al. (2016). In the actual calculation, N, P_2O_5, and K_2O are purified from compound fertilizers at the weight of 17%, 17%, and 17%; from water-soluble fertilizers at the weight of 32%, 21%, and 9%; and from organic fertilizers at the weight of 2%, 1%, and 2%. Then the inorganic parts of N, P_2O_5, and K_2O fertilizers formed synthetic chemical fertilizer, and the organic parts formed purified organic fertilizer.

As far as pesticides, the field research revealed that apple farmers use different types of pesticides in their orchards, as shown in Table 1, including fungicides, insecticides, and herbicides, the inputs of which were 10.10, 1.84, and 1.47 kg/ha, accounting for 76.87%, 12.87%, and 10.26% of the total pesticide inputs, respectively. In this study, we refer to Khoshnevisan et al. (2014) and Yuan et al. (2019) to calculate the total amount of pesticides according to active ingredients. In the data calculation process, based on the input data from the apple farmers, we refer to the relevant standards about the active ingredients labeled on the package, and firstly calculate the amount of active ingredients of the most frequently used individual pesticides, such as mancozeb, carbendazim, chlorothalonil, chlorpyrifos, omethoate, and atrazine, which are calculated according to the active ingredient weights of 80%, 40%, 75%, 40%, 40%, and 45%, respectively; secondly, the weighted average of the pesticides belonging to the same type is obtained. For example, mancozeb, carbendazim, and chlorothalonil are all fungicides; chlorpyrifos and omethoate are insecticides; and atrazine is herbicides.

We also can see the input of diesel consumption was 534 kg/ha in Table 1. In orchard operations, agricultural machinery such as tractors and agricultural tricycles play an important role in plowing, fertilizer application, pesticide spraying, and daily transportation. However, the running of agricultural machinery is mainly dependent on diesel consumption. Therefore, diesel consumption represents to a large extent the degree of mechanization of the apple orchard, which was calculated by consumption amount of per unit time and actual working time of the machinery used, according to Khoshnevisan et al. (2014). In the specific calculation process, we take peasant household as the measurement unit since different farmers usually use different practices. Firstly, we clarify the different types of machinery used by each household and their corresponding models and power, which are the key factors affecting the diesel consumption, and accordingly determine the diesel consumption of each type of machinery per unit of time. Secondly, the actual working time of each type of machinery in the apple orchard is combined to calculate the total amount of diesel consumption for individual machinery. Finally, the total diesel consumption of all the machines are summed up and the average value of operating 1 ha of apple orchard is calculated based on the actual area of orchards cultivated.

As for irrigation water, it is mainly influenced by natural precipitation. In years with high rainfall, irrigation water use is relatively low; on the contrary, in years with low rainfall, farmers usually choose to increase the frequency of irrigation to mitigate the risk caused by drought. We learned from field research that in 2020, the study area was a year of slight drought, and farmers usually only needed to irrigate 1–2 times to meet the water demand of apple trees, with annual water consumption of 545,000 L per hectare (see Table 1).

Moreover, human labor is also an important input factor because apple production is a labor-intensive activity, the input of which was 9360 h/ha in Baishui County (see Table 1). Since fertilization, pesticide spraying, flower thinning, fruit thinning, bagging, and fruit picking are highly seasonal, and the demand for labor is relatively concentrated in these stages, families with a small workforce usually choose to hire laborers. In addition, daily management like plowing, weeding, pruning, and irrigation are usually finished by their own labor. Therefore, the labor input in this study includes both hired labor and home-based labor. In the field research, our questionnaire was developed with a year as the production cycle, involving plowing, weeding, pruning, irrigation, fertilization, pesticide spraying, flower thinning, fruit thinning, bagging, picking, etc. The number of labor inputs, the number of working days, and the number of hours of labor per day are counted in detail for each stage. In the process of calculation, the total number of labor hours for each stage is calculated by the number of laborers (persons) × working days (days) × labor hours per person per day (hours/persons·days), then the total labor hours for all stages are summed up, and finally, the input of average human labor for 1 ha of the orchard is obtained according to the cultivated area. It should be noted that in the actual situation in rural China, minors aged 12–18 years usually help their families in agricultural production during the busy season, and older people aged 61–75 years still participate in moderate labor, while laborers aged 19–60 years are considered the normal labor force. Therefore, the study of Wang et al. (2019) is referred to calculate the number of labor input, and the labor members in the age groups of 12–18 and 61–75 were discounted by 0.2 and 0.5 times of the normal labor force, respectively, according to their labor ability.

Life cycle assessment method

The LCA method, as an important tool to support global sustainable development programs, has a relatively wide application in producing a particular product in agricultural sector. A typical LCA study consists of four steps, goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation of results (ISO 14044 2006).

Goal and scope definition

The main goal of this study is to assess the EB and the potential HCL produced by the APS in Baishui County of Shaanxi Province, then explore and propose feasible mitigation options. The system boundary of this study includes the agricultural materials production and the farming subsystems (Fig. 1). The former mainly refers to the production of N, P_2O_5, and K_2O, pesticides, and diesel for agricultural machinery and equipment, etc., while the latter mainly refers to fertilization, pesticide spraying, irrigation, weeding, pruning, flower and fruit thinning, bagging, harvesting, etc. The functional unit (FU) is set to operate 1 ha of the apple orchard.

As recommended by the crucial reviews for LCA applied to perennial cropping systems (Bessou et al. 2013; Cerutti et al. 2014; Alaphilippe et al. 2016; Alishah et al. 2019), the unproductive stages (i.e., orchard creation and establishment and the first 3 years of sapling growth) and the productive stage (i.e., years with apple commercialization) were included in the analysis. The nursery stage has been

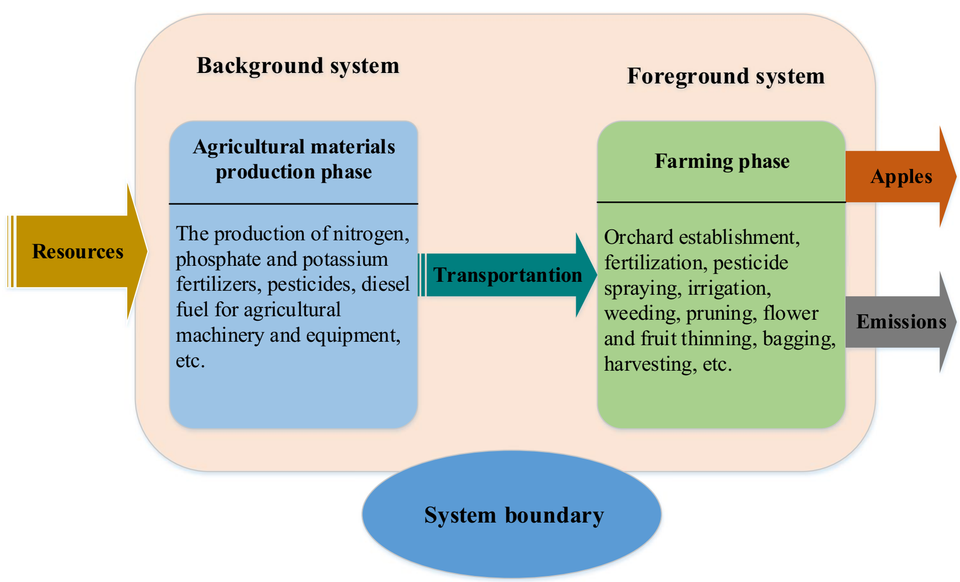

Fig. 1 System boundary for a life cycle assessment of the apple production system

excluded in this study, mainly due to the lack of reliable data regarding this phase of apple-growing, which would not significantly affect the final results as the longevity of the crops and the small percentage of annual tree replacement (Vázquez-Rowe et al. 2012; Vinyes et al. 2017).

Furthermore, it should be noted that agricultural machinery and equipment play an essential role in apple production, but the production of agricultural machinery is not considered in the system boundary of this study, and only the influence of fuel consumption during the use of machinery is considered. There are two reasons for this: firstly, the operation of agricultural machinery mainly relies on fuel consumption especially diesel; machinery itself usually does not produce pollutant emissions in the process of use, but diesel combustion causes pollutant emissions, so the focus should be on the impact of diesel consumption in the process of machinery use rather than the impact of machinery itself. Secondly, agricultural machinery such as tractors and tricycles are not disposable consumer goods and with a useful life of about 10–20 years, and which owned by a household is generally used not only for apple production but also for food crop production and other agricultural activities; the share of use allocated to apple production is not major in terms of the whole life cycle of the machinery.

Life cycle inventory analysis

In the LCA study, the LCI quantifies all the inputs and outputs of the studied system according to the FU and system boundary considered throughout the product's life cycle. The survey questionnaires that described farming practices are used to establish an inventory of farming inputs for the APS, and the outputs including emissions to air, water, and soil are calculated according to the previous research findings and the background data system. The detailed information of the LCI generated in different phases is shown in Table 2, and includes energy consumption and emissions of various pollutants, which are aggregated from the inputs data in Table 1 and the corresponding emission factors of each input substance. In order to be consistent with the system boundary of the study, we calculate the inventory data involved in the two phases separately first, and then sum up.

For the agricultural materials production phase, the inventory data are calculated by drawing on the research results of Liang (2009), combining with data from field research. Different emissions such as carbon monoxide (CO), carbon dioxide (CO_2), ammonia (NH_3), nitrogen dioxide (N_2O), nitrate (NO_3), sulfur oxides (SO_x), and methane (CH_4) in the production of N, P_2O_5, and K_2O from chemical fertilizers, pesticides, and diesel for agricultural machinery and equipment are calculated using the input data for 1 ha of apple orchard in Table 1, and the corresponding emission factors are listed in Tables S2–S6. It should be noted that emissions caused by the organic fertilizer production are not considered. Because the organic fertilizer used in this study is mainly dried sheep dung, which is made by farmers who dry the wet manure from the animals they raise and without industrial processing, therefore it does not cause significant pollutants.

For the farming phase, the pollutant emission parameters from different operational measures such as fertilizer application, pesticide application, irrigation, and orchard management are mainly derived from the relevant research results published by previous authors. There are large differences between chemical and organic fertilizers in terms of the impacts generated by fertilization. For chemical fertilizers, NH_3 volatilization and NO_3 leaching are 8.74% and 17.21% of N input in the apple production area of Shaanxi Province, respectively (Ge et al. 2014; Zhu et al. 2018), and direct N_2O emissions is 3.01% of N input (Wen et al. 2016). Relatively speaking, these three types of emissions including NH_3 volatilization, NO_3 leaching, and direct N_2O emissions from organic fertilizers are smaller, and accounted for 2.68, 14.42, and 0.78% of the N input, respectively. Besides, it is important to note that indirect N_2O emissions can also occur from NH_3 volatilization and NO_3 leaching, with values of 1% and 2.5%, respectively (Brentrup et al. 2004). According to Zhu et al. (2018), the data on phosphorus losses in orchards is relatively lacking, so the national average P loss (0.2% of inorganic and organic P_2O_5 input) is used in this study. Moreover, emissions of CO, CO_2, nitrogen oxide (NO_x), SO_x, CH_4, chemical oxygen demand, and biochemical oxygen demand produced during the application of fertilizers are calculated based on Ji et al. (2012). In addition, the heavy metal content in different fertilizers are calculated based on Liang (2009) and Feng et al.(2017). The corresponding emission factors mentioned above are listed in Tables S7–S8.

Apple production is also greatly dependent on pesticide use, leading to environmental hazards and health risks (Simon et al. 2011). Referring to Van Calker et al. (2004), the pollutants entering the air, soil, and water are calculated as 10%, 43%, and 1% of the active ingredient the pesticide use, respectively. According to the finding of Liang (2009), the pollutant emissions from the use of diesel for agricultural machinery are calculated. The heavy metal content brought by irrigation water in orchards is calculated based on Lei et al. (2020). In addition, the orchard operation requires a lot of human labor input, such as flower and fruit thinning, bagging and picking, and apple picking, all of which are more labor-intensive. Referring to Nguyen and Hermansen (2012), an emission factor of 0.7 kg CO_2 eq/man·h is used to calculate the environmental impact of labor inputs. In the calculation of each input inventory, the results are used of multiplying the inputs in Table 1 with the corresponding emission factors listed in Tables S9–S12.

Table 2 Life cycle inventory of apple production in Baishui County, Shaanxi Province

Item	Agricultural materials production phase (kg/ha)	Farming phase (kg/ha)	Total (kg/ha)
Energy consumption	8.98×10^{4} MJ	–	8.98×10^{4} MJ
HC (hydrogen carbonate)	6.50×10^{-1}	1.55×10^{-2}	6.66×10^{-1}
CO (carbon monoxide)	4.46	9.35×10^{-1}	5.39
CO_2 (carbon dioxide)	9.33×10^{3}	1.04×10^{4}	1.97×10^{4}
NH_3 (ammonia)	1.94	6.45×10^{1}	6.64×10^{1}
N_2O (nitrogen dioxide)	2.14×10^{-1}	2.61×10^{1}	2.63×10^{1}
NO_x (nitrogen oxide)	3.26×10^{1}	2.99×10^{1}	6.25×10^{1}
NO_3 (nitrate)	–	1.36×10^{2}	1.36×10^{2}
SO_x (sulfur oxides)	2.90×10^{1}	4.50	3.35×10^{1}
CH_4 (Methane)	5.54×10^{-1}	3.2910^{-1}	8.83×10^{-1}
P_{tot} (total phosphate)	1.34	1.39	2.73
NH_4 (ammonium nitrate)	1.42×10^{1}	–	1.42×10^{1}
COD (chemical oxygen demand)	7.54×10^{1}	1.46	7.69×10^{1}
BOD (biochemical oxygen demand)	1.98	1.20×10^{-1}	2.10
As (arsenic)	3.32×10^{-5}	5.45×10^{-4}	5.78×10^{-4}
Cu (copper)	3.89×10^{-5}	4.61×10^{-2}	4.62×10^{-2}
Zn (zinc)	3.15×10^{-4}	6.32×10^{-1}	6.32×10^{-1}
Cd (cadmium)	8.27×10^{-6}	1.83×10^{-3}	1.83×10^{-3}
Pb (lead)	1.20×10^{-4}	2.84×10^{-2}	2.86×10^{-2}
Cr (chromium)	–	3.27×10^{-3}	3.27×10^{-3}
Hg (mercury)	–	1.63×10^{-4}	1.63×10^{-4}
PM_{10} (inhalable particle matter)	4.18	5.12×10^{-1}	4.69
Pesticides to air	–	1.43	1.43
Pesticides to water	–	1.43×10^{-1}	1.43×10^{-1}
Pesticides to soil	–	6.13	6.13
Waste residue	2.26×10^{4}	–	2.26×10^{4}
Dust	1.30×10^{2}	–	1.30×10^{2}
Waste water	1.93×10^{3}	–	1.93×10^{3}

The substances such as energy consumption, waste residue, dust, and waste water are not applicable in the CML-IA baseline method, which is also present in Table 2 to ensure the integrity and transparency of the inventory date. The definitions are represented in parentheses, and they are consistent in Table 3, so which not repeated note where they appear later to avoid duplication

Life cycle impact assessment

The third step of LCA is the LCIA. The purpose of conducting an impact assessment is to identify the main environmental issues of the production system and the contribution potential to environmental impacts caused by different production phases. In this study, the CML-IA baseline methodology is used to analyze the environmental effects, which includes the following 11 main environmental impact categories: acidification (AC), abiotic depletion (AD), abiotic depletion (fossil) (AD(FF)), eutrophication (EU), freshwater aquatic ecotoxicity (FAE), global warming (GW), human toxicity (HT), marine aquatic ecotoxicity (MAE), ozone layer depletion (OLD), photochemical oxidation (PO), and terrestrial ecotoxicity (TE).

Specifically, the results of impact assessment include three steps: characterization, normalization, and weighting. Characterization generally uses equivalent coefficients to calculate the potential environmental impacts caused by the same type of pollutant, and the relevant results to a specific impact category can be presented with the contribution potential values and the actual LCIA values. Normalization values are generally the average levels of global (ornational or regional) resource consumption and environmental emissions, and different types of environmental impact were directly compared after normalization. The weighting values are usually obtained to compare comprehensive impact values; the step can aggregate each individual environmental potential to form a total index. Various environmental impact categories are of different importance to sustainable development, which needs to be weighted. An important note is that the results of this study do not involve comparative analysis between different environmental impact categories and comprehensive impact result analysis, but rather focus on analyzing contribution potential values and the actual LCIA values; therefore, the characterization results are used.

In addition, the ReCiPe 2016 method was applied to evaluate the end-point life cycle environmental impacts entailing damage to human health from pollutants generated by the APS in this study, and DALYs constituted the index of human health losses (Huijbregts et al. 2017). The HCL approach is an advanced method that uses life-cycle thinking to link environmental pollutants to human health and economic cost indicators. Drawing on the model construction of Liang et al. (2019), Wang and Lu (2020), and Wang and Zhao (2019), the following equations were set up for calculating and assessing potential HHR and HCL.

$$PDTHH_i = DF \times Dose_i \tag{1}$$

$$HHR = \sum PDTHH_i \tag{2}$$

$$HCL = PC\_GDP \times HHR \tag{3}$$

where $PDTHH_i$ is the potential damage caused by the ith pollutant to human health; $Dose_i$ is the dose of the ith pollutant; and DF_i is the damage factor of the ith pollutant (DALY kg^{-1}), and the meaning of DALY denotes the years that are lost or associated with a disability caused by a disease or accident. In addition, PC_GDP denotes China's per capita GDP in 2020 is approximately 72,447 Chinese yuan (CNY).

Results

Environmental impact analysis

Figure 2 shows the environmental impact contribution of 1 ha of the apple orchard on different phases. The environmental impact of the agricultural materials' production phase is more significant, with an overall average contribution potential of 56.04%, while the farming phase is relatively small, with an overall average contribution potential of 43.96%. Among all environmental impact categories, the agricultural materials' production phase has a greater impact on AD of 7.69×10^{-1} kg Sb eq, MAE of 1.30×10^{7} kg 1,4-DB eq, and GW of 1.94×10^{4} kg CO_2 eq, with a share of the total 95.66%, 89.50%, and 75.66%, respectively, while the farming phase mainly has a greater impact on TE of 3.43×10^{5} kg 1,4-DB eq, AC of 3.37×10^{2} kg SO_2 eq, and EU of 1.14×10^{2} kg PO_4 eq, with a share of the total 99.09%, 80.37%, and 79.30%, respectively. The actual LCIA values mentioned above are listed in Tables S13.

In order to further investigate which substances are actually responsible for the different environmental impact categories, this study considers substances from both phases for environmental impact analysis. Figure 3 illustrates the environmental impacts of inputs for operating 1 ha of the apple orchard, and the corresponding actual LCIA values are listed in Tables S14.

In the agricultural materials production phase, N production has the largest impact on the GW impact category, with a contribution potential of 59.11%; it also has a greater impact on MAE, AD, HT, FAE, and AD

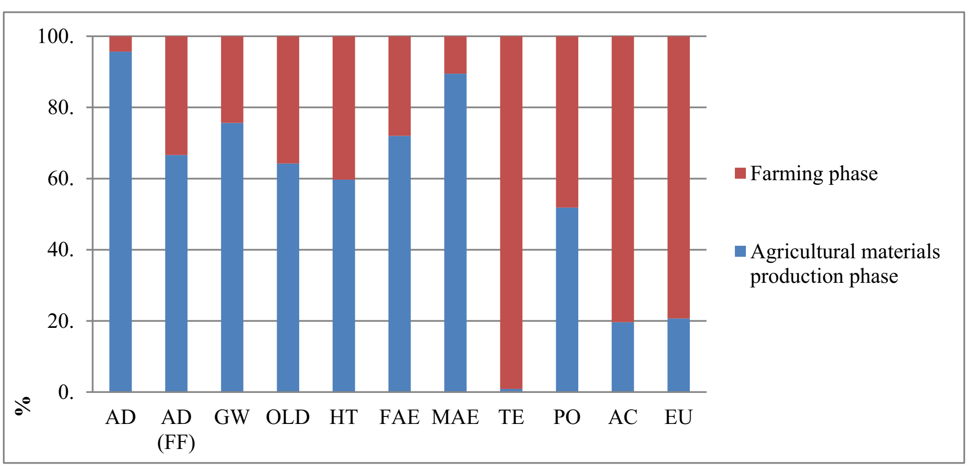

Fig. 2 The environmental impact contribution of 1 ha of the apple orchard on different phases. AD, abiotic depletion; AD (FF), abiotic depletion (fossil fuels); GW, global warming; OLD, ozone layer depletion; HT, human toxicity; FAE, freshwater aquatic ecotoxicity; MAE, marine aquatic ecotoxicity; TE, terrestrial ecotoxicity; PO, photochemical oxidation; AC, acidification; EU, eutrophication. The meanings of acronyms are represented in the abovementioned are consistent in Fig. 3, so they are not repeated note where they appear later to avoid duplication

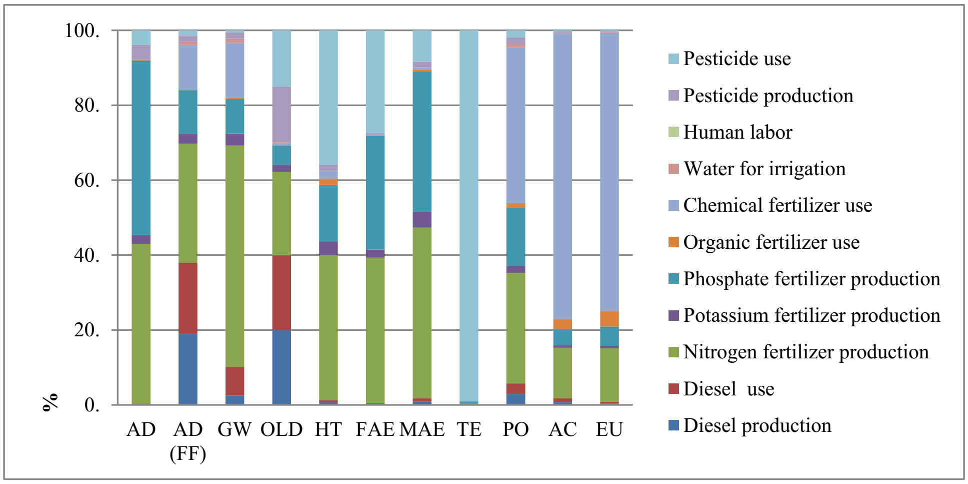

Fig. 3 Environmental impacts of different inputs for operating 1 ha of apple orchard

(FF), with a contribution potential of more than 30%. P_2O_5 production mainly has a greater impact on AD, MAE, and FAE, with contribution potentials of 46.66%, 37.45%, and 30.29%, respectively. Relatively, K_2O has a little impact on the environment, and its largest contribution among all environmental impact categories is MAE, with an impact potential of only 4.20%. Pesticide production mainly contributes to the OLD impact category, with an impact potential of 14.93%, while its contribution to other categories is small. Diesel production has a greater impact on OLD and AD (FF), with an impact potential of 19.97% and 18.96%, respectively. The analysis of the above results shows that N production is the most important environmental hotspot in the agricultural materials production phase. This is largely determined by the N demand for the orchard operation, and the reliability of this conclusion is corroborated by the input profile at the farming phase.

In the farming phase, the use of chemical fertilizer has a more significant impact on AC, EU, and PO, and the contribution potentials are as high as 76.25, 74.17, and 41.44%, respectively. Compared with other impact categories, the use of organic fertilizer also has a greater impact on AC and EU, but the contribution potentials are only 2.67 and 4.21%, respectively. The use of pesticides dramatically impacts TE, with a contribution potential of 99.08%, and also has a greater impact on HT and FAE, with a contribution potential of 35.87 and 27.39%, respectively. Diesel use mainly impacts OLD, AD (FF), and GW, with contribution potentials of 19.97, 18.96, and 7.66%, respectively. It is worth noting that the impact of irrigation water and labor input on the environment is almost negligible. Hence, the use of chemical fertilizer is the most important environmental hotspot in the farming phase.

Human capital loss assessment

Calculations performed using Eq. (1) showed that the PDTHH per ha for the APS varied based on damage factors and doses of pollutants. Table 3 presents the main pollutants and their contribution to potential damage to human health. As Table 3 shows, among the midpoint indicators of ReCipe 2016, CO_2 has the largest potential damage to human health, which is 1.83×10^{-2} DALY/ha, followed by NH_3 of value which is 1.00×10^{-2} DALY/ha; the third is N_2O with a value of 7.29×10^{-3} DALY/ha. It can also be seen from Table 3 that among the top 5 significant pollutants (CO_2, NH_3, N_2O, NO_3, SO_x) that cause potential damage to human health, the damage category of fine particulate matter formation accounts for three, and the damage category of global warming accounts for two.

According to Eqs. (2) and (3), the value of HHR and HCL caused by pollutants can be obtained. As shown in Table 4, among the three endpoint indicators of ReCipe 2016, the HHR values of global warming, fine particulate matter formation, and human toxicity are 2.56×10^{-2}, 2.73×10^{-2}, and 5.48×10^{-3} DALY/ha·year, respectively; the total value is 5.84×10^{-2} DALY/ha·year. Among them, fine particulate matter formation has the greatest impact, accounting for 46.74% of the total HHR. On the contrary, the impact of human toxicity is the smallest, accounting for only 9.39% of the total HHR.

As Table 4 shows, the HCL value of operating 1 ha of the apple orchard for 1 year is about 4230 CNY. According to statistics, the total apple planting area in Baishui County in 2020 was 36,700 ha, creating a total output value of 4.8 billion CNY. It can be calculated that the total HCL caused by the APS in Baishui County in 2020, by combining the

Table 3 Main pollutants and their contributions to potential damage to human health

Pollutants	Damage category	Damage factor (DALY/kg)	PDTHH/1 ha (DALY/ha)
CO_2	Global warming	9.28×10^{-7}	1.83×10^{-2}
N_2O	Global warming	2.77×10^{-4}	7.29×10^{-3}
CH_4	Global warming	3.16×10^{-5}	2.79×10^{-5}
NH_3	Fine particulate matter formation	1.51×10^{-4}	1.00×10^{-2}
NO_X	Fine particulate matter formation	6.92×10^{-5}	4.32×10^{-3}
NO_3	Fine particulate matter formation	5.03×10^{-5}	6.83×10^{-3}
SO_X	Fine particulate matter formation	1.82×10^{-4}	6.10×10^{-3}
As	Human toxicity	1.49×10^{-3}	8.61×10^{-7}
Cu	Human toxicity	4.24×10^{-6}	1.96×10^{-7}
Zn	Human toxicity	8.60×10^{-3}	5.43×10^{-3}
Cd	Human toxicity	2.28×10^{-2}	4.18×10^{-5}
Pb	Human toxicity	2.39×10^{-4}	6.83×10^{-6}
Cr	Human toxicity	1.79×10^{-9}	5.85×10^{-12}
Hg	Human toxicity	2.67×10^{-3}	4.36×10^{-7}

Table 4 The results of human health risk and human capital loss for apple production system

Items	HHR (DALY)	HCL (CNY)	
	1 ha	1 ha	Total area in 2020
Global warming	2.56×10^{-2}	1.86×10^{3}	6.81×10^{7}
Fine particulate matter formation	2.73×10^{-2}	1.98×10^{3}	7.26×10^{7}
Human toxicity	5.48×10^{-3}	3.97×10^{2}	1.46×10^{7}
Total	5.84×10^{-2}	4.23×10^{3}	1.55×10^{8}

research results in this study with statistical data, is about 155 million CNY, accounting for 3.23% of the total output value of apples this year.

Discussion

Mitigation options

An important finding is that chemical fertilizer use is the most significant environmental hotspot in apple production, so we try to develop feasible mitigation options with a principal focus on chemical fertilizers. The excessive use of chemical fertilizers leads to the waste of resources and brings water eutrophication, degrades soil quality, and further increases greenhouse gas emissions (Zhang et al. 2011). Therefore, in 2017, the Ministry of Agriculture of China put forward the "Action plan for the substitute of chemical fertilizers with organic fertilizers for fruit, vegetable and tea," vigorously advocating the replacement of chemical fertilizers with organic fertilizers in apple planting.

Experiments have shown that apple orchards with organic fertilizers have significantly improved fruit appearance and internal quality, solid soluble content increased by 10 ~ 20%, peel anthocyanin content increased by 20 ~ 30%, and vitamin C content increased by 10 ~ 30%, and the sugar-acid ratio is increased by 20 ~ 50% (Kai and Adhikari 2021). At the same time, the fruit color is brighter, the palatability is better, and the commodity value is improved. In addition, increasing the application of organic fertilizer can also enhance crop resistance, reduce the damage of pests and diseases, and reduce the number of pesticides, which is ultimately conducive to improving the quality and efficiency of apple production in the long term (Zhu et al. 2018).

In 2020, China's Ministry of Agriculture and Rural Affairs further put forward the "Notice on replacing chemical fertilizers with organic fertilizers for fruit, vegetable and tea." The notice clearly stated that the use of chemical fertilizers in the core demonstration area should be reduced by more than 15%, and the use of organic fertilizers should be increased by more than 20%. However, field research data shows that there is still a big room for development between the status quo of apple farmers and the policy goals for replacing chemical fertilizers with organic fertilizers in the current.

This study conducted a scenario analysis based on the above policy background, combined with the important finding of chemical fertilizer use which is the most critical environmental hotspot. Assuming that other conditions remain unchanged, the fertilization situation of farmers in the survey area will be simulated. The scenario simulation in this study is that the use of chemical fertilizer is reduced by 15%, and the organic fertilizer consumption increases by 20%. The changes in environmental impact and HCL in scenario analysis are presented below.

Changes in environmental impact

Figure 4 shows the percentage change for different environmental impact categories under the scenario of a 15% reduction in chemical fertilizer use and a 20% increase in organic fertilizer use, except for the three impact categories of AD, FAE, and TE; all other impact categories show a downward trend, among which AC, EU and PO have a relatively obvious decrease, with 14.72, 13.99 and 8.07%, respectively; the decrease of other impact categories within 3%. It is worth noting that in this scenario analysis, the category of FAE increased by 0.03%, which indicates that with the increase of organic fertilizers, the FAE shows a relatively weak increase. The increased use of organic fertilizers can lead to the risk of heavy metal contamination of water resources, which is consistent with Zhu et al. (2018).

Changes in human capital loss

Table 5 shows the changes in HHR and HCL under the scenario simulation. For HHR, a 15% reduction in the use of chemical fertilizers and a 20% increase in the use of organic fertilizers resulted in a reduction in the categories of global warming, fine particulate matter formation, and human toxicity damage, with 1.71×10^{-3}, 3.33×10^{-3}, and 1.01×10^{-3} DALY/ha·year, respectively, and the corresponding reduction rates are 6.67, 12.21, and 18.34%, respectively. The total value of HHR decreased by 6.05×10^{-3} DALY/ha·year, and the reduction rate is 10.36%, which means that replacing chemical fertilizer with organic fertilizer under the situation of scenario analysis can reduce the risk of human health by 10.36%.

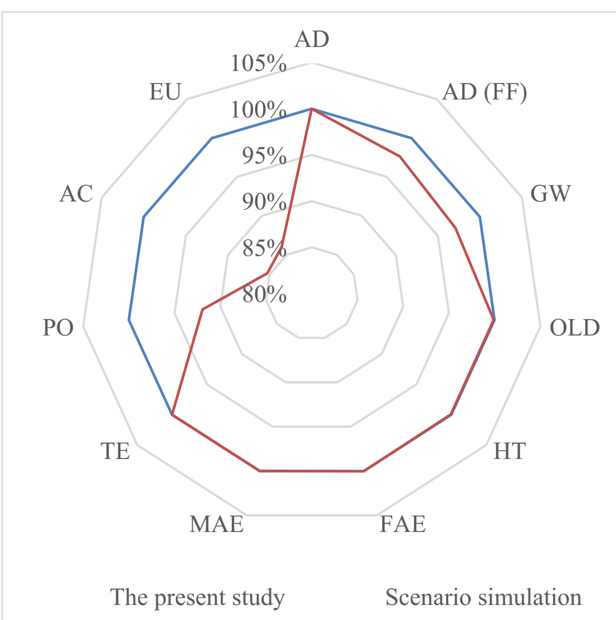

Fig. 4 Percentage changes of different impact categories under scenario simulation

Table 5 Changes in human health risk and human capital loss under scenario simulation

	HHR (DALY)	HCL (CNY)	
Items	1 ha	1 ha	Total area in 2020
Global warming	-1.71×10^{-3}	-1.24×10^{2}	-4.54×10^{6}
Fine particulate matter formation	-3.33×10^{-3}	-2.41×10^{2}	-8.86×10^{6}
Human toxicity	-1.01×10^{-3}	-7.29×10^{1}	-2.67×10^{6}
Total	-6.05×10^{-3}	-4.38×10^{2}	-1.61×10^{7}

For the HCL, as show in Table 5, the categories of global warming, fine particulate matter formation, and human toxicity damage are reduced by about 124, 241, and 73 CNY, respectively; and the total HCL is reduced by about 438 CNY, a reduction rate of 10.36%, after the replacing chemical fertilizer with the organic fertilizer in scenario simulation. Combined with the apple planting situation in Baishui County in 2020 (total area was 36,700 hectares), it can be calculated that the overall HCL is decreasing about 1.61×10^{7} CNY, under the situation of a 15% reduction in the use of chemical fertilizers and a 20% increase in the use of organic fertilizers for all apple farmers in Baishui County.

Implications of mitigation options

The results show that of all the agricultural inputs of apple production, chemical fertilizer use is the most significant environmental hotspot and contributes most to pollutant-induced HCL, which is consistent with the study of Wang and Zhao (2019). Therefore, finding feasible alternatives for further improving the efficiency of fertilizer application should be an effective way to reduce EB and pollutant-induced HCL from APS in the study area. Furthermore, the scenario analysis results in this study show that after the use of chemical fertilizers is reduced by 15% and the use of organic fertilizers increases by 20%, as the goal set by China's Ministry of Agriculture and Rural Affairs, both in environmental impacts and HCL, it can get a clear improvement. Therefore, the insight is that replacing chemical fertilizers with organic fertilizers has positive effects on the environment. Other studies have shown that some positive environmental externalities were produced when replacing chemical fertilizers with organic fertilizers, which not only benefits the green and low-carbon development of the apple planting industry (Zhao et al. 2014), but also make corresponding contributions on the sustainable development of the entire agricultural production system (Chen et al. 2018). The results are consistent with our findings.

However, there is one question that deserves deeper consideration. Whether the replacement of chemical fertilizers with organic fertilizers will result in some detrimental effects, such as a decrease in yield. It is probably the most significant concern for apple growers and policymakers. Since yield is a direct determinant of sales revenue for farmers, a decrease in yield would largely mean a decrease in economic income, which they are unwilling to accept. For policymakers, potential yield loss either would lead to a price increase or cannot meet local and global demand, which may lead to economic implications. In real-life practice, the answer to the above question seems to be no, and there are two main reasons for this. Firstly, from the policy background, the policy related to the substitution of chemical fertilizers with organic fertilizers in apple production was first proposed in 2017 in China. Twenty-five apple-growing counties were selected for piloting in the country. The pilot counties were increased to more than 50 in 2018. The share of organic fertilizers substituted for chemical fertilizers was determined by 2020 and promoted nationwide; this important decision was made by the policymakers based on the specific practical results of the previous pilot phase, which is the result of a comprehensive weighing of various possible relevant factors, of which yield is the top priority. Secondly, from the scientific research results, it has been shown that the replacement of chemical fertilizer with organic fertilizer does not cause a decrease in apple yield in the short term. And it is beneficial to increasing yield, improving quality, enhancing soil fertility, and alleviating agricultural surface pollution, with income and environmental effects in the long term, because the effectiveness of applying organic fertilizers has a certain time lag (Zha 2022).

For other detrimental effects, it may be true that there are more or less. The study of Zhu et al. (2018) showed that there is a high content of metal ions in organic fertilizers, which has the possibility to lead to the consequence that soil eco-toxicity potential increased; however, the one envisaged 50% replacement of fertilizer application with compost in their study, and the weight of substitution is much higher than our study from policy goals. Therefore, we believe that the proportion of organic fertilizers replacing chemical fertilizers would not cause very serious adverse effects as long as it is within a reasonable range.

The above analysis shows that the substitution of organic fertilizers with chemical fertilizers does not have some detrimental effects, such as decreased yield and increased soil eco-toxicity potential. However, the implementation plan of replacing chemical fertilizers with organic fertilizers has not yet achieved the expected policy goals at the present stage. So there is a curious question of why some apple growers are not enthusiastic about adopting organic fertilizers. According to the survey and research results, it is known that the replacement of chemical fertilizers with organic fertilizers may increase the investment cost in the short term because organic fertilizers are usually more expensive than chemical fertilizers, and the application effect has a time lag after the performance, which increases discouragement for some apple farmers to use organic fertilizers since farmers usually tend to focus more on short-term interests in the present (Chen et al. 2018).

Based on the above discussion, we believe that some policy implications should be presented. Firstly, government departments should set up special subsidies for the farmers who use organic fertilizers in apple orchards. The results of environmental impacts and HCL in the current study can provide some reference for the development of subsidy standards. It has been shown that agricultural subsidies are one of the most frequently used policy measures, especially in the initial stages of the promotion of new agricultural technology and practice, as they can largely reduce the risk aversion of farmers due to uncertainty (Chen et al. 2020). In terms of implementation effects, a large number of studies have shown that agricultural subsidies worldwide have a positive influence on the development of agriculture (Chen et al. 2017; Lameck et al. 2019). More specifically, there is a study that showed that the weighted environmental impact index decreased by 11% and human health impact decreased by 23.2% per ha for the winter wheat-summer maize rotation system after the promotion of the agricultural subsidy policy in Huantai County of Shandong province in China, largely as a result of improved management of nitrogen fertilizers, and the subsidy for conservation agricultural practices is the main support for the success of such improvements (Liang et al. 2019).

Secondly, local agricultural bureaus should increase their efforts to publicize the policy and raise farmers' awareness of the potential benefits in adopting organic fertilizers through the establishment of demonstration households, increased training, and field teaching, thereby ensuring that the policy goal of replacing chemical fertilizers with organic fertilizers is achieved in apple-growing areas. It has been shown that one of the disadvantages of the smallholder production model is that it takes longer for farmers to recognize and receive something new such as new agricultural technologies and practices (Chuanmin and Falla 2006), so a proper understanding of the long-term impact of organic fertilizer application by increasing policy advocacy and strengthening training efforts for farmers is often the main grip for policy implementation (Chen et al. 2022).

Thirdly, technical demonstration departments in apple planting areas should strengthen their technical capacity and then take efforts to promote and demonstrate organic fertilizer application technology services. Fourthly, apple farmers should raise their awareness of environmental protection and risk of HCL, actively adopt low-carbon technologies such as organic fertilizer application, and focus on environmental protection and human capital enhancement while ensuring economic returns.

Limitations and future applications

There are several limitations to this study, which may have affected the results to a certain degree. In terms of calculating LCI, especially for the indicators of the emissions generated by various inputs, the present study is in line with the general practice of most scholars (Keyes et al. 2015; Alaphilippe et al. 2016; Vinyes et al. 2017; Bartzas et al. 2017; Zhu et al. 2018), and mainly refers to the empirical values provided by previous studies, since field measurements in the apple orchards have some challenges. However, such an approach may lead to different results compared with field measurements. Therefore, future research should continuously improve the LCI indicators, combining field trial measurement data and empirical data under the objective conditions allowed, with a view to improving the accuracy of the inventory indicators. A further limitation is that we only considered 11 pollutants including AD, AD (FF), GW, OLD, HT, FAE, MAE, TE, PO, AC, and EU; others such as energy and land depletion are excluded, because these are out of the scope of the CML-IA baseline method chosen for this study, which makes the results to be somewhat conservative. In addition, we focus only on the potential impacts caused by the substitution of chemical fertilizers with organic fertilizers when conducting the scenario analysis, because chemical fertilizer use proved to be the most important environmental hotspot in apple production. However, we do not focus on the possible impacts caused by the other substitutions of other inputs, like increasing labor and irrigation water while decreasing fertilizers and pesticides in scenario analysis, mainly because such substitutions seem unrealistic in the current Chinese apple production system; at the same time, we assume that apple yields would remain unchanged. However, replacing chemical fertilizers with organic fertilizers could increase production efficiency and yields would likely increase significantly (Zhao et al. 2014). In order to simplify the analysis process, we did not consider the possible degree of variation in apple yield.

Despite these limitations, this study is still valuable in terms of applicability. The study gives an intuitive picture of how apple production processes affect environment and human health. This is helpful for the identification key environmental hotspots and optimization of inputs of apple production, which can further help to promote the sustainable development of China's apple industry. Besides, the HCL approach can be applied to other kinds of agricultural production systems and it can also be extended to other regions worldwide. Based on this research, future studies can develop some newer research perspectives. Along with the continuous technological progress, the input factors in apple production may change, and it is one of our future research directions to further explore the environment as well as human health impacts caused by the substitution of different factors.

Conclusions

In this study, the CML-IA baseline method and the ReCiPe 2016 method of LCA are used to analyze and evaluate the potential EB and the HCL of the APS in China for the first time. Baishui County, which is located in Shaanxi Province, a typical apple production area in China, is selected for the research area and 1 ha of the apple orchard is taken as the FU. The study finds that the production of N and the use of chemical fertilizers are the main reasons for the EB in the agricultural materials production and farming phases, respectively. Specifically, the agricultural materials production phase has a more significant impact on AD, MAE, and GW; the farming phase mainly has a more significant impact on TE, AC, and EU. Besides, apple cultivation and management can cause pollutant-induced HCL, mainly the chemicals used in apple orchards produce a range of pollutant emissions, which not only affect the environment, but also have impact on human health. The top 5 major pollutants in the potential damage to human health caused by the APS are CO_2, NH_3, N_2O, NO_3, and SO_x. Operating 1 ha of the apple orchard for one year can cause 5.84×10^{-2} DALY of HHR and the corresponding HCL is about 4230 CNY. Furthermore, to replace chemical fertilizers with organic fertilizers can effectively reduce the detrimental environmental impacts and HCL caused by the APS. The conclusions of this study indicate that, in order to promote the green, low-carbon, and sustainable development of the apple industry, it is imperative to further promote the effective implementation of the plan of organic fertilizers to replace chemical fertilizers for apple farmers in China.

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Author contribution Juanjuan Cheng: investigation, data curation, formal analysis, validation, writing original draft, writing review and editing. Qian Wang: investigation, data curation, conceptualization, visualization, writing review and editing. Jin Yu: conceptualization, methodology, validation, supervision, writing review and editing.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval Ethical approval was obtained from the School of Economics and Management, Northwest Agriculture and Forestry University.

Consent to participate Not applicable.

Consent to publish Not applicable.

Competing interests The authors declare no competing interests.

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