

Lifecycle environmental benefits of integrated rational fertilization, biochar, and constructed wetland in mitigating nutrient loading

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ABSTRACT

Agricultural activities due to fertilization contribute significantly to nutrient loadings and other environmental burdens, posing a severe threat to ecosystems. Although a portfolio of green agricultural practices is recommended, few studies address the environmental benefits from a life-cycle perspective. This study comprehensively evaluates the cradle-to-gate environmental benefits of integrating rational fertilization, biochar, and constructed wetlands (CWs) exemplified by plum cultivation. Four assessment scenarios were designed: (S1) conventional cultivation, (S2) rational fertilization with biochar amendment, (S3) conventional cultivation with a simulated CWs system, and (S4) rational fertilization with biochar amendment and a simulated CWs system. In the assessment, rational fertilization used half the fertilizer compared to conventional practices, biochar was applied at 0.1 ton/ha, and horizontal subsurface flow CWs were filled with washed gravel and planted with *Phragmites australis*. The findings show that rational fertilization combined with biochar (S2) or CWs (S3) alone show about half the eutrophication impacts of conventional cultivation (S1). Combining rational fertilization, biochar and CWs (S4) further reduces freshwater and marine eutrophication potentials by ~73.5% and ~69.8%, respectively. Similarly, these green agricultural practices (either S2 or S4) effectively reduce the overall endpoint impacts by about 47%, with synergistic improvements, particularly in endpoint freshwater ecotoxicity and freshwater eutrophication, observed for S4 (a significant reduction of 76%) compared to S1. Regarding the carbon footprint, the production of plums using conventional agriculture emits ~300 kg CO₂-eq per ton-plum, whereas using green agricultural practices results in only ~138 kg CO₂-eq per ton-plum, representing a reduction of 45.8% in greenhouse gas emissions. This study highlights the potential of green agricultural practices to mitigate NPS nutrient loadings to aquifers and achieve sustainable agricultural management through reduced global warming and other environmental impacts.

1. Introduction

Nutrient runoff from agricultural activities poses a significant threat to water quality, soil health, and human well-being. As highlighted by Luna Juncal et al. (2023), the excessive use of chemical fertilizers can lead to nutrient pollution in waterways. When chemical fertilizers enter local streams, rivers, and groundwater via erosion, infiltration, or irrigation, nitrogen and phosphorus levels in water bodies increase. This

stimulates rapid algal growth, leading to eutrophication (Ockenden et al., 2017; Yu et al., 2020) and blooms of toxic cyanobacteria (Kruk et al., 2023). Zhou et al. (2022) underscored the vulnerability of shallow lakes in agricultural and densely populated areas to nutrient pollution. The shallow depth of these lakes, combined with high levels of human activity and external nutrient inputs, makes them particularly susceptible to eutrophication and other water quality issues. The far-reaching consequences of nutrient pollution extend to terrestrial ecosystems,

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impacting both ecosystems and human populations. Global fertilizer consumption increased from ~177 million tonnes in 2011 to ~195 million tonnes in 2023 (Statista 2024), emphasizing the urgent need for sustainable agricultural practices that minimize nutrient runoff and protect water resources.

Resources must be used efficiently, and agricultural inputs must be managed properly to achieve sustainable agricultural development, improve soil health, and enhance farmer livelihoods (Sarfranz et al., 2023). However, Blume et al. (2016) noted that only one-third to one-half of applied nitrogen fertilizer is utilized by plants during the growing season, with the rest lost as nitrate ions in runoff or as nitrous oxide (N₂O) and ammonia (NH₃) emissions. Excessive use of chemical fertilizers also contributes to soil erosion (Samijan et al., 2024). Borrelli et al. (2017) estimated that irrational fertilization increases soil erosion by 50.5 %. Conversely, Wang et al. (2021b) noted that rational fertilization sustains bacterial and archaeal abundance, enhances bacterial community structure, and promotes soil fertility and rice yield for red paddy soil. Lenoir et al. (2023) also observed that rational nitrogen fertilization ensures high yields and a rational nitrogen supply. Samijan et al. (2024) studied the application of organic, inorganic, and bio-fertilizers for sorghum productivity on drylands in Indonesia. They found that balanced fertilization provides sufficient nutrients to the soil, increases nutrient adsorption availability, and boosts yields by about 21–36 %. Ji et al. (2024) reported that the average nitrogen concentration in lake sediments in China has increased by 267 % since 1850. However, with proper nutrient cycle control, nitrogen concentrations in Chinese lakes could decrease by 87 % in southern districts and by 19 % in northern districts between 2030 and 2100. Rational fertilization, combined with effective green agricultural practices, reduces nutrient levels in farmland, freshwater ecosystems, and the broader environment, fostering a more sustainable future.

Biochar is another widely used approach to control agricultural nutrient loading. Using appropriate amounts of high-quality biochar in soil stores organic carbon and increases crop yields and soil fertility (Wang et al., 2016). Biochar can also be used as an adsorbent, fuel, or catalyst (Woolf et al., 2021). Its characteristics, including low density and high porosity, enable it to retain significant nutrients (Angst et al., 2013). These properties allow biochar to release nutrients slowly while improving water retention, promoting seedling growth (Altland and Krause, 2012; Briggs et al., 2012). Guo et al. (2021) demonstrated that biochar application (50 tonnes/ha) significantly improved nutrient uptake in tomatoes compared to non-biochar treatment, with nitrogen uptake increasing by 74–80 % and phosphorus uptake by 76–95 %. Zhao et al. (2024) studied the benefits of different sources of biochar-rice straw biochar, co-pyrolysis pig manure and rice straw biochar (CPB), and pig manure biochar-on non-point source pollution mitigation. Compared to the business-as-usual scenario, biochar treatments reduced TN (37–47 %) and TP (36–41 %) loadings, with CPB showing the greatest reduction. CPB also significantly improved rice yield and biomass accumulation compared to conventional fertilizer ($p < 0.05$).

In addition to rational fertilization and biochar as fertilizer amendments, structural management practices, such as constructed wetlands (CWs), mitigate nutrient loadings in agricultural surface runoff. CWs are an environmentally friendly and cost-effective ecological restoration technology with a high capacity for nutrient removal and recovery (Kamilya et al., 2022). Nutrients are removed via a combination of physical and biological processes. As water flows through a wetland, suspended nutrients are physically filtered out by the soil and vegetation. Wetland plants play a vital role in nutrient uptake by absorbing nutrients from the water for their growth and development (Vymazal, 2020). Microorganisms within the wetland ecosystem also contribute significantly to nutrient removal by decomposing organic matter and releasing nutrients into the water. CWs are widely used for wastewater treatment and the restoration of water ecosystems (Ferreira et al., 2017; Vymazal, 2019). Vymazal et al. (2020) used various surface areas, substrate types, and distances from the surface to create three types of CWs

for cleaning tile drainage, achieving an average nutrient removal rate of ~1510 kg per ha per year. Lin et al. (2023) noted that CWs decrease the greenhouse gas (GHG) emission fluxes and that denitrifying inoculation alleviates N₂O emissions. Cun et al. (2024), Yang et al. (2024) and Page et al. (2023) also conducted studies on CWs to purify agricultural runoff. Page et al. (2023) restored wetlands in an intensive agricultural region, achieving two-year mean retention efficiencies of 46 ± 13 % for TP and 47 ± 8 % for TN. Cun et al. (2024) filled CWs with a mixture of iron-carbon and organic solid substrates, resulting in superior removal efficiencies of TN (52–58 %), TP (68–70 %), and chemical oxygen demand (57–70 %).

To determine the comprehensive environmental effects of green control technologies, including rational fertilization, biochar, and CWs for nutrient loading mitigation, a robust method is essential. Conventional experiments often involve immediate use scenarios and compare before-and-after effects. However, these methods do not account for the environmental burdens associated with the manufacturing processes of these technologies. Life-cycle assessment (LCA) provides a holistic approach to evaluate environmental impacts across the entire lifespan, making it suitable for applications at governmental, industry, and consumer levels (Denora et al., 2023; Owsianiak et al., 2018). Denora et al. (2023) applied life cycle-based indicators to assess precision nitrogen management in rainfed durum wheat cultivation. LCA also identifies environmental hotspots - processes with the most significant impacts - and highlights areas for improvement. These results enable manufacturers to identify product weaknesses, optimize resource selection, and drive innovation.

To the best of our knowledge, several papers have simultaneously considered green agricultural practices. Saxena et al. (2024) studied the effect of different levels of pine needle biochar fortified with various dosages of fertilizer. Jia et al. (2024) highlighted the synergistic effect between biochar and nitrate fertilizer. Several studies have also explored the benefits of CWs in purifying agricultural water (Fan et al., 2024; Guerrero-Brotons et al., 2024; Vymazal et al., 2023). Although significant research has been conducted on the individual environmental benefits, few studies have comprehensively discussed them from an LCA perspective. This has resulted in a lack of consideration for both positive and negative effects. Therefore, this study aims to use LCA to determine the environmental benefits of rational fertilization, biochar, and CWs in mitigating nutrient loading from fruit-growing land, compared to conventional agricultural practices. By integrating LCA, this study provides a comprehensive understanding of the long-term environmental benefits of these practices. Additionally, we evaluate the mitigation of global warming potential (GWP), eutrophication, and other environmental impact indicators. The integration of biochar, CWs, and rational fertilization can enhance soil fertility, improve water retention, and reduce nutrient runoff, all of which are key to promoting environmentally friendly farming practices. Lastly, by evaluating these approaches, this study highlights their potential in achieving a more sustainable and resilient agricultural system.

2. Methods

2.1. Study area and set-up

The uneven temporal and spatial distribution of rainfall necessitates reliance on reservoir storage and regulation to maintain a stable water supply. However, increased development in the watersheds of reservoirs and the intensification of agricultural activities mean that the water in major reservoirs in the country is often subject to eutrophication, primarily due to excessive nutrient loading. In Taiwan, where agricultural activities are intensive, the total amount of organic and chemical fertilizer used in 2021 was approximately 1.1 million tonnes, with chemical fertilizer accounting for around 80 % of the total. To determine the effect of upstream agricultural activities on the environmental quality of water bodies, this study selects suitable locations in the nutrient-rich

Shimen Reservoir upstream area. Rational fertilization and biochar application are tested *in situ*, while CWs are simulated under controlled conditions to assess the environmental benefits of green agricultural activities. The study aims to evaluate the performance of nutrient loading control technologies and the effectiveness of measures to prevent pollution in the study area. Upstream of the Shimen Reservoir, agricultural activities are intense, with crop cultivation being the predominant agricultural practice. Red-fleshed plums, a crop with a long cultivation history in the Shimen Reservoir upstream region, are the target crop for this study. The planting season lasts from January to May, with an average temperature of 18.8 ± 4.8 °C ($n = 147$), an average monthly precipitation of 107 ± 94 mm ($n = 5$), and an average water temperature of 21.2 ± 2.4 °C ($n = 20$). The soil texture is classified as sandy loam or loam, exhibiting good drainage capacity and low clay content. The overall soil density is approximately 1.08 ± 0.05 g/cm³, and the porosity is around 50 % (National Taiwan University 2022). These characteristics suggest that plants can effectively root downward without being affected by soil compaction or viscosity. The agricultural fields are located approximately 4.46–5.08 km from the reservoir.

As shown in Fig. 1, this study outlines four assessment scenarios: conventional cultivation (Scenario 1, or S1), rational fertilization (half-dose) combined with biochar amendment (Scenario 2, or S2), conventional cultivation with a simulated wetland purification system (Scenario 3, or S3), and rational fertilization (half-dose) with biochar amendment and a simulated wetland purification system (Scenario 4, or S4). Each scenario involves a planting area of approximately 485 m². The crop cultivation process follows the recommendations of the Taiwan Good Agriculture Practice Development Association. Prior to cultivation, the farmland was prepared, and biochar was mixed with the base fertilizer. During the planting period, three to four topdressings were applied at intervals of 20–40 days. The total cultivation period lasted 140 days, after which the crops were harvested.

This study employs a combination of rational fertilization, biochar, and system simulations with CWs to filter agricultural surface runoff. The biochar used in this study was produced through electrical pyrolysis of bamboo at 750 °C, and the biochar exhibited a pH of 8.5 and a BET specific surface area of 0.031 m²/g (National Taiwan University 2022). Biochar was blended with fertilizer and incorporated into the soil to sequester organic carbon via carbon fixation and to enhance crop yield and soil fertility. Over extended periods (ranging from decades to

millennia), biochar remains stable in the soil (Wang et al., 2016). Due to the small volume of agricultural surface runoff, the surface runoff treatment capacity of CWs was designed to be 1 m³ per day and includes a primary treatment (i.e., septic tank), followed by horizontal subsurface flow (HSSF) CWs. Owing to their low energy requirements and ease of operation and maintenance, HSSF CWs have increasingly replaced conventional CWs (Puigagut et al., 2007). Lab-scale studies of HSSF CWs have shown an increase in BOD removal rates (Corbella and Puigagut, 2018). The CWs were filled with washed gravel (20–50 mm in diameter) and planted with *Phragmites australis* (Corbella et al., 2017; Pedescoll et al., 2013). *Phragmites australis* is widely used in CWs because it increases hydraulic retention time, allowing more time for the filtration and adsorption of nutrients and pollutants. Compared to other plants, such as *Typha angustifolia*, *Phragmites australis* is less likely to clog the system.

2.2. Data collection

The organic fertilizer contains 5.5 % total nitrogen, 2.0 % total phosphorus, 2.0 % total potassium oxide, 85 % organic matter and 13 % moisture content. This fertilizer, a plant residue-based product, is a blend of castor bean meal, rapeseed meal, rice bran, soybean meal, coconut meal, sesame meal, and other ingredients. To evaluate the nutrient impact, this study measured the concentrations of nitrogen and phosphorus. Since the impact of methane emissions is significantly outweighed by the increases in N₂O and CO₂ (Kasimir-Klemetsson et al., 1997), it is considered negligible and thus excluded. The nitrogen and phosphorus contents are calculated at different stages to assess the effect of fertilizer application on the environment, particularly concerning surface water runoff. Table 1 provides the details of fertilizer application for each scenario, along with the total nitrogen and phosphorus loss to the water body and the amount of N₂O emitted into the air.

To determine the degree to which nitrogen and phosphorus are mitigated in freshwater, this study excavated soil to a depth of 20–30 cm next to the crop and placed infiltration water collection plates. Surface runoff was collected from the test area using custom-made runoff collectors. The soil was then backfilled to restore the original conditions. The collectors were placed approximately 50 cm away from the nearby crops, with two sets of runoff collectors at each sampling point to ensure

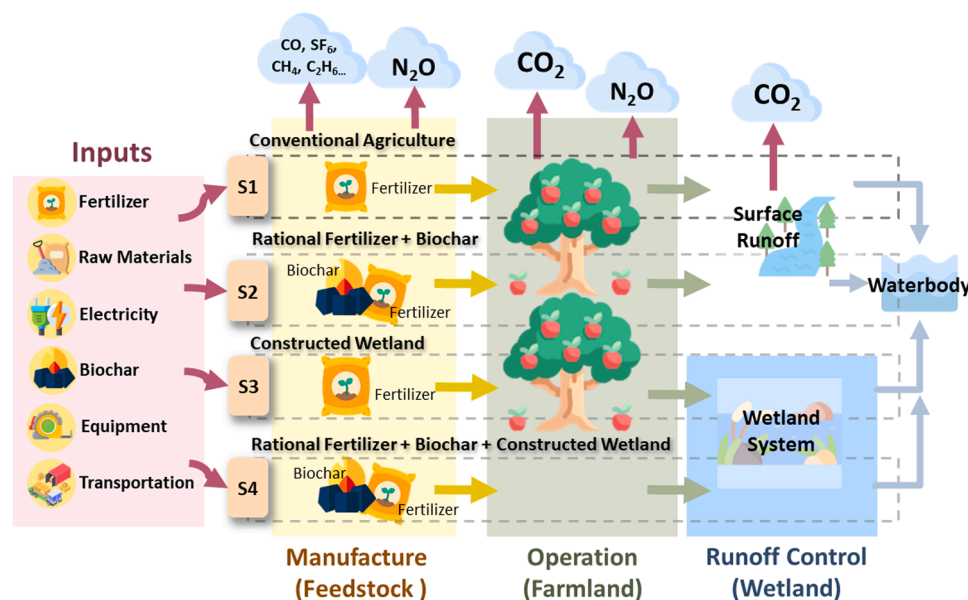


Fig. 1. System boundary of four scenarios (i.e., S1, S2, S3, and S4) for integrated rational fertilization, biochar, and constructed wetland (CW) in mitigating agricultural non-point source (NPS) pollution.

Table 1
Inventory data for different life-cycle stages in this study.

Category	Stage	Condition ^a	Scenario (Unit: kg/ha) ^b			
			S1	S2	S3	S4
Fertilizer	Base	nitrogen fertilizer, as N	110	110	110	110
		phosphate rock, as P ₂ O ₅ , beneficiated	40	40	40	40
		biochar	0	100	0	100
	Topdressing 1	nitrogen fertilizer, as N	198	99	198	99
		phosphate rock, as P ₂ O ₅ , beneficiated	72	36	72	36
	Topdressing 2	nitrogen fertilizer, as N	143	71.5	143	71.5
		phosphate rock, as P ₂ O ₅ , beneficiated	52	26	52	26
	Topdressing 3	nitrogen fertilizer, as N	143	71.5	143	71.5
		phosphate rock, as P ₂ O ₅ , beneficiated	52	26	52	26
	Topdressing 4	nitrogen fertilizer, as N	66	0	66	0
phosphate rock, as P ₂ O ₅ , beneficiated		24	0	24	0	
Total	nitrogen fertilizer, as N	660	352	660	352	
	phosphate rock, as P ₂ O ₅ , beneficiated	240	128	240	128	
	biochar	0	100	0	100	
Harvest Discharge	Crop	Harvesting plum weight (yield)	32,990	37,113	32,990	37,113
		Runoff	TN in runoff	41.84	22.32	20.83
	TP in runoff		6.0	3.2	2.37	1.26
	Gas Emission	N ₂ O emission	6.60	2.74	6.60	2.74

^a TN: total nitrogen; TP: total phosphorus.

^b The experimental data was gathered from the literature (National Taiwan University, 2022).

sufficient runoff collection. The sampling frequency followed the principle of collecting samples after the first rainfall following fertilization, within 24 hours. Sampling was adjusted according to the actual field conditions, with the rainfall accumulation required to be at least 10 mm and within an average range of $\pm 25\%$. The sample collection methodologies follow the guidelines of MOE Taiwan (2017). The report by MOE Taiwan (2022) calculates the amount of N₂O emissions from farmlands as:

$$N_2O_{direct\ emission} = \frac{44}{28} \times (F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \times EF \times (100 - BR) \quad (1)$$

where F_{SN} is the amount of nitrogen fertilizer that is applied to the soil (kg), F_{ON} is the amount of organic nitrogen that is applied to the soil (kg), F_{CR} is crop residue nitrogen (kg), F_{SOM} is nitrogen mineralization resulting from the loss of mineral soil organic carbon due to changes in land use or management practices, EF is the N₂O-N emission factor from nitrogen inputs to upland fields (kg-N per kg of nitrogen input), and BR is the N₂O removal ratio (%) due to the use of biochar in croplands. In terms of the BR value, Zhang et al. (2024) calculated the effect of using biochar using a mean annual precipitation of more than 1200 mm in a cropland and measured a reduction in N₂O emissions of 22.1 %.

2.3. Life cycle assessment

Before calculating the LCA results, the system boundaries must be defined. Consistency in setting system boundaries for each scenario is essential to ensure that the calculated results are representative and can be compared meaningfully. The selection of an appropriate functional unit (FU) for the study is also crucial, as a suitable FU enables a meaningful comparison between scenarios. Impact assessment indicators must be applied, followed by a comprehensive interpretation and analysis of the results. The LCA calculation process follows ISO (2006) guideline. The LCA computation involves four distinct steps: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation.

2.3.1. Definition of scope and functional unit

This study considers and compares the life-cycle emissions of plum cultivation across four scenarios. Fig. 1 shows the scope and system boundaries of the LCA, which begins with fertilizer manufacturing and ends with the final plum yield. It includes raw materials, manufacturing,

and CWs purification. During the manufacturing phase, this study considers the environmental impact of fertilizer, biochar, CWs, and other raw material feedstock acquisition, electricity consumption for the manufacturing process, emissions, and transportation. Biochar feedstock is agricultural waste, so there are no GHG emissions from feedstock acquisition. This experiment examines whether the use of fertilizer and biochar reduces nutrient pollution from agricultural surface runoff. Therefore, the agricultural phase only considers nutrient salt emissions resulting from fertilizer application. The emissions from constructing a CW that purifies one m³ of water per day are also considered. The nutrient salt emissions (mainly nitrogen and phosphorus) from the water after purification by CWs are calculated. Since the main goal of this study is to quantify the nutrient loading mitigation efficiency of green practices, it is preferable to choose per hectare as the FU. This FU more comprehensively accounts for land use phenomena and measures the land use efficiency of different agricultural methods, helping to prevent yield bias. While inappropriate fertilizer use might achieve short-term yield gains, it can harm soil health and worsen conditions for crop growth. The per hectare approach also provides a better assessment of farming's impact on the overall ecosystem.

2.3.2. Life cycle inventory

The emissions for the fertilizer manufacturing phase are calculated using the Ecoinvent 3.6 database (Wernet et al., 2016). This study focuses on the application of nitrogen and phosphate fertilizers. The input data is shown in Error! Reference source not found. The nutrient loss data is based on experimental measurements. The emissions and carbon reduction benefits for the use of biochar and CWs are derived from the calculation results of the studies by Woolf et al. (2021), Corbella et al. (2017), Li et al. (2022) and Zhang et al. (2024).

The data for biochar utilization and emissions comes from the study by Woolf et al. (2021). The study includes information on the biochar production process (e.g., biomass source and pyrolysis temperature), environmental conditions during application (e.g., ambient temperature and soil pH), and considerations for GHG emissions from the soil for a century after the use of biochar. Relevant data is presented, and the formulas are described as follows:

$$GHG_{bc} = \frac{44}{12} \bullet M_{bc} \bullet F_C \bullet F_{perm} + 0.23 \bullet n \bullet GWP_{N_2O} \quad (2)$$

where GHG_{bc} is the net figure for avoided GHG emissions in units of CO₂-eq (CO₂e), M_{bc} is the mass of biochar added to soil, F_C is the organic

carbon fraction of the biochar, F_{perm} is the fraction of biochar organic carbon that remains after a specific period of time (100 years for this function), n is the baseline annual N_2O emissions (emissions regardless of biochar utilization) and GWP_{N_2O} is the GWP for N_2O (i.e., 273) according to the study by Masson-Delmotte et al. (2021).

Table 2 presents the input materials and parameters of CW. The emissions for CWs manufacturing are sourced from the study by Corbella et al. (2017). Background data comes from the Ecoinvent 3.1 database (Moreno Ruiz et al., 2016; Weidema et al., 2013). The wetland purification efficiency is taken from the study by Li et al. (2022), which uses a neural network to analyze the existing CW purification data and calculates the corresponding purification efficiency for different situations. The CWs for this study are small, so the residence time for water in the wetlands is short. Therefore, the evaporation of water during the CW stage and the discharge during the CW maintenance stage are negligible and therefore excluded from calculations.

2.3.3. Life cycle impact assessment

Environmental effects refer to the adverse short-term or long-term impacts that human activities have on air, land, water, and ecosystems as a whole. A life cycle impact assessment includes steps such as characterization, normalization, and weighting of the calculation methods. This study utilizes Umberto LCA+ (version 10.0.3, ifu, Germany) combined with the ReCiPe 2008 Midpoint and Endpoint methodology to evaluate environmental effects. This method performs impact assessments over a 100-year horizon. From the results, the most relevant indicators for nutrient loadings were identified. Ultimately, four midpoint indicators and five endpoint indicators were selected. The four midpoint indicators are GWP100, GWP500, marine eutrophication potential, and freshwater eutrophication potential. The five endpoint indicators are: (1) ecosystem quality, climate change, ecosystems; (2) human health, total; (3) human health, climate change; (4) ecosystem quality, freshwater ecotoxicity; and (5) ecosystem quality, freshwater eutrophication. The results align with the goals and scope of this study.

2.4. Sensitivity analysis

The environmental sensitivity analysis provides a structured framework for objectively evaluating the potential for significant environmental impacts (González Del Campo, 2017). A sensitivity analysis was carried out to determine how variations in fertilizer application rates influence environmental outcomes. This study compares two scenarios: conventional agricultural practices and a scenario incorporating biochar application. Data quality was verified by assessing the environmental impact of fertilizer usage at $\pm 20\%$ and $\pm 50\%$ variations from the standard rate. This approach helps clarify the relationship between fertilizer use levels and environmental impacts, offering valuable insights into optimizing agricultural practices.

Table 2

Design parameters for CWs with a treatment capacity of one m^3 per day.

Materials	Value	Unit	Parameter
Concrete	0.0000175	m^3	Concrete, normal (Wang et al. 2021a,b) production
Metals	0.000842	kg	Steel, low-alloyed, hot rolled (Stewart et al., 2017) production
Coating	0.0000119	kg	Extrusion, plastic pipe (Stewart et al., 2017) production
Plastics	0.00792	kg	Polyethylene, high density, granulate (Stewart et al., 2017) production
Gravel & sand	2.76	kg	Sand gravel 50:50 - market for sand CH; market for gravel, round CH
Bricks	0.0386	kg	Market for clay brick RoW

References: (Corbella et al., 2017; Moreno Ruiz et al., 2016; Weidema et al., 2013)

3. Results and discussion

3.1. Material flow analysis in farmland

According to Table 1, the discharge from each scenario shows significant variation. In S1, the discharge of TN and TP in surface runoff is ~ 41.8 kg-N/ha and ~ 6.0 kg-P/ha, respectively. With the implementation of rational fertilization and biochar (S2), the discharge of TN and TP decreases by approximately 46.7%. Additionally, N_2O emissions are reduced by about 54.3% with the application of rational fertilization and biochar. Furthermore, the inclusion of CWs further reduces nutrient loading in runoff. In S4, TN in runoff decreases by approximately 52.2%, while TP in runoff decreases by roughly 60.2%. These findings demonstrate that the combination of rational fertilization, biochar, and CWs can effectively reduce nutrient loading in surface runoff by 70–74%. Singh et al. (2015) and Mahmoudi et al. (2024) also use HSSF CWs to purify water bodies. Singh et al. (2015) studied highway runoff treatment and found that HSSF CWs could remove $\sim 77\%$ of phosphorus and $\sim 78\%$ of NH_3-N . Mahmoudi et al. (2024) applied HSSF CWs for dairy wastewater treatment in Tunisia, achieving high removal efficiency. This study selected HSSF CWs for simulation, and the results align with the aforementioned studies, confirming that this type of CWs can effectively reduce nutrient loadings.

Fig. 2 shows the Sankey diagrams for conventional agriculture and the use of rational fertilization with biochar, illustrating nutrient transport in the farmland phases. In conventional agriculture, crop nitrogen uptake is only 57%, but when rational fertilization is combined with biochar, the nitrogen uptake rate significantly increases to 89%. This confirms that biochar acts as an effective soil conditioner by enhancing soil fertility, improving soil structure, and increasing the crop's ability to absorb nutrients. Rational fertilization further boosts this effect by optimizing nutrient balance for the crops, improving nutrient availability, and reducing nutrient imbalances. Regarding nitrogen loss, biochar reduces conversion loss to just 5%, compared to 36% in conventional agriculture. This indicates that biochar not only helps crops utilize the nitrogen already present in the soil but also minimizes nitrogen loss through volatilization or leaching, thereby enhancing nutrient use efficiency. For phosphorus, the uptake rate in conventional agriculture is only 9%, indicating that phosphorus fertilizer is not being efficiently utilized. However, with biochar application, the crop's phosphorus uptake rate increases to $\sim 63\%$. This significant improvement demonstrates that biochar enhances the soil's ability to retain phosphorus and improves its availability to crops. Additionally, the conversion loss for phosphorus is reduced from 89% to 27%, further emphasizing biochar's role in improving nutrient retention and uptake. Rational fertilization contributes to this improvement by supplying essential nutrients in appropriate amounts, reducing phosphorus fixation, and enhancing crop nutrient absorption. Based on previous research, several studies have pointed out that biochar can increase nutrient retention, soil fertility, and nutrient uptake (Angst et al., 2013; Guo et al., 2021; Zhao et al., 2024), which are similar to the findings reported in this study.

3.2. Midpoint impact assessment

This study divides the midpoint impact into manufacturing and farmland phases, and the total midpoint impacts are calculated. During the manufacturing phase, the production of fertilizer and biochar is considered; during the farmland phase, the impact of fertilizer application is included. Table 3 presents the midpoint impact results for different scenarios using the ReCiPe methodology. The results show that S1 and S3, as well as S2 and S4, use the same fertilizer manufacturing process; therefore, they have nearly identical values for the manufacturing phase. However, slight differences are observed in several midpoint impacts of the manufacturing phase, such as fossil depletion, marine ecotoxicity, human toxicity, and climate change.

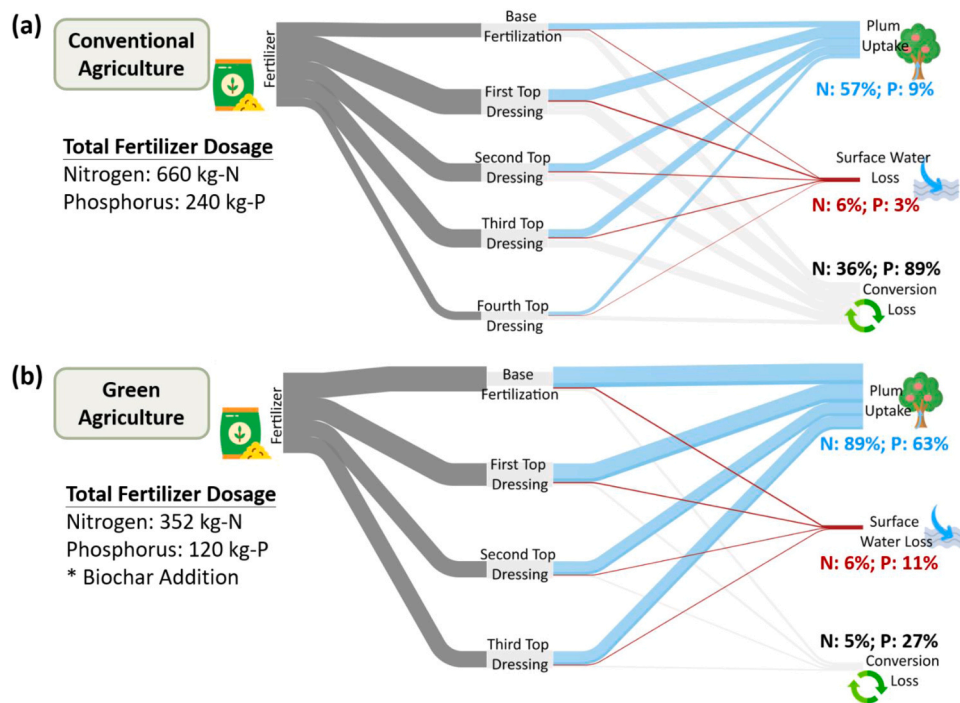


Fig. 2. Sankey diagram of nutrient flow on farmlands for (a) conventional farming system, and (b) green agricultural practices.

Table 3

Life-cycle midpoint impact for different scenarios using the ReCiPe methodology (functional unit: per ha).

Midpoint	Unit	S1		S2		S3		S4	
		Manufacture	Farmland	Manufacture	Farmland	Manufacture	Farmland	Manufacture	Farmland
Terrestrial ecotoxicity	kg 1,4-DCB-Eq	164.02	-	87.48	-	164.02	-	87.48	-
Terrestrial acidification	kg SO ₂ -Eq	49.93	-	26.79	-	49.93	-	26.79	-
Ozone depletion	kg CFC-11-Eq	3.57E-04	-	1.90E-04	-	3.57E-04	-	1.90E-04	-
Water depletion	m ³ water-Eq	138.00	-	73.75	-	138.29	-	73.75	-
Fossil depletion	kg oil-Eq	1185.49	-	632.29	-	1185.52	-	632.29	-
Ionizing radiation	kg U ₂₃₅ -Eq	320.16	-	170.76	-	320.17	-	170.76	-
Marine ecotoxicity	kg 1,4-DCB-Eq	136614.71	-	72862.09	-	136615.62	-	72862.09	-
Freshwater ecotoxicity	kg 1,4-DCB-Eq	319.99	-	170.66	-	319.99	-	170.66	-
Particulate matter formation	kg PM ₁₀ -Eq	12.13	-	6.52	-	12.13	-	6.52	-
Climate change, GWP500	kg CO ₂ -Eq	5659.12	1009.80	3075.26	419.22	5659.18	1009.80	3075.26	419.22
Urban land occupation	m ² a	4145276.78	-	2210814.29	-	4145276.78	-	2210814.29	-
Agricultural land occupation	m ² a	1809.15	-	964.88	-	1809.15	-	964.88	-
Freshwater eutrophication	kg P-Eq	1.20	6.00	0.64	3.20	1.20	2.37	0.64	1.27
Photochemical oxidant formation	kg NMVOC-Eq	45.40	-	24.44	-	45.40	-	24.44	-
Natural land transformation	m ²	-0.38	-	-0.20	-	-0.38	-	-0.20	-
Human toxicity	kg 1,4-DCB-Eq	83047.27	-	44292.53	-	83047.92	-	44292.53	-
Metal depletion	kg FE-Eq	938.65	-	500.62	-	938.65	-	500.62	-
Marine eutrophication	kg N-Eq	6.56	41.84	3.51	22.32	6.56	20.83	3.51	11.12
Climate change, GWP100	kg CO ₂ -Eq	7929.39	1966.8	4286.08	816.52	7929.46	1966.8	4286.08	816.52

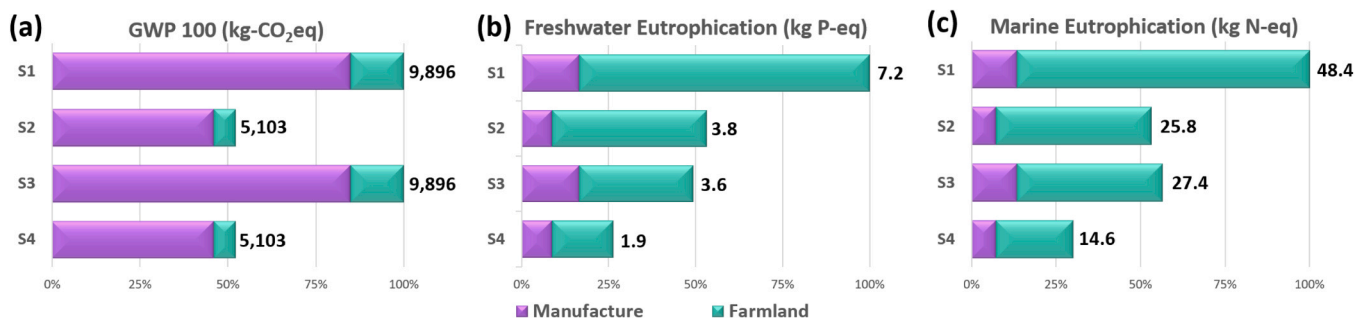


Fig. 3. Midpoint impact assessment for different scenarios: (a) global warming potential (GWP 100), (b) freshwater eutrophication (kg P-eq), and (c) marine eutrophication (kg N-eq).

These differences arise from emissions caused by the construction of the CW. Additionally, the CWs in this study only treat agricultural surface runoff water, and because the volume of surface water flow is small, the CW is constructed on a very small scale (~1 CMD). Consequently, the emissions generated during the construction of CW are much smaller than those from fertilizer production. Manufacturing for CW construction represents less than 1 % of the overall environmental midpoint impact. Despite its small scale, the CW significantly reduces freshwater and marine eutrophication, achieving an estimated 50 % reduction in freshwater eutrophication and a 43 % reduction in marine eutrophication.

Fig. 3 compares several key midpoint impact indicators across each scenario and between the two phases. In terms of climate change (kg CO₂-eq), it shows that S2 and S4 have only half the GWP-100 (a ~48 % reduction) compared to S1, indicating that rational fertilization combined with biochar significantly reduces GWP. Among these scenarios, the manufacturing phase accounts for the majority of GWP 100 and GWP 500, contributing 80–88 % of the total. The GWP 500 for the farmland phase is approximately 4–13 % higher than the GWP 100 value, suggesting that the environmental impact of the farmland phase is likely to increase over time. Additionally, CWs do not significantly reduce GWP, likely because the environmental impacts from their construction are offset by the reductions they achieve. It should be noted that the time scale of assessment considered in this study is limited to only one cultivation period, which amplifies the environmental impacts of the CW construction stage over the entire life cycle.

In terms of freshwater eutrophication (kg P-eq) and marine eutrophication (kg N-eq), both S2 and S3 show about half the environmental impact of S1. Rational fertilization combined with biochar (S2) and CWs (S3) can mitigate the freshwater eutrophication impacts by 47 % and 50 %, respectively. When these green agricultural practices are further combined (S4), a positive synergy is observed. S4 achieves only one-quarter of the freshwater (~26.5 %) and marine (~30.2 %) eutrophication impacts compared to S1. Moreover, the farmland phase remains the major contributor to these eutrophication midpoint impacts. Freshwater eutrophication caused by S1 during the farmland phase is 87.5 % higher than that of S2 and is 5 times greater than emissions from the manufacturing phase. Marine eutrophication caused by S1 is ~48.4 kg N-eq, with the farmland phase accounting for ~41.8 kg N-eq (86.4 %). The use of CWs (S3) is shown to mitigate eutrophication impacts on agricultural surface runoff water, thereby reducing freshwater

and marine eutrophication caused by the farmland phase by ~50 % compared to S1. Freshwater eutrophication caused by S4 is only ~26.5 % of that caused by S1, and marine eutrophication is reduced to ~30.2 %. These results demonstrate that rational fertilization and the use of biochar in conjunction with CW purification systems effectively mitigates eutrophication impacts on freshwater and marine environments.

3.3. Endpoint impact assessment

Table 4 presents the results of life-cycle endpoint impact assessment across different scenarios, and Fig. 4 illustrates the comparison of endpoint impacts attributed to the manufacturing and farmland phases between S1 (the business-as-usual reference) and other scenarios. The results indicate that the primary endpoint impact is on ecosystem quality, rather than human health or resource depletion (see Fig. 4(a)). Compared to S1, the use of biochar combined with rational fertilization (S2) reduces the total endpoint impacts by ~47 %, including a ~54 % reduction in effects on human health (see Fig. 4(b)). CWs (S3) alone do not contribute to a reduction in endpoint impacts on total ecosystem quality or total human health, as shown in Fig. 4(b-d). However, CWs (S3) effectively reduce endpoint impacts on ecosystem quality in terms of "freshwater ecotoxicity (Fig. 4(e))" and "freshwater eutrophication (Fig. 4(f))" by 47–48 %. While CWs are effective in mitigating certain ecosystem-related impacts, the majority of freshwater endpoint impacts still arise from the farmland phase. In contrast, most of the damage to human health is linked to the manufacturing phase. Interestingly, biochar appears to be more effective than CWs in improving human health outcomes, as CWs lead to only minimal reductions in their impact on human health. Additionally, although S2 and S4 exhibit similar reduction potentials in total endpoint impacts (Fig. 4(a)), synergistic improvements in endpoint freshwater ecotoxicity and freshwater eutrophication are observed for S4, with a significant reduction of 76 % compared to S1, as shown in Fig. 4(e-f).

3.4. Sensitivity analysis

To determine the long-term environmental impact of fertilizer usage, this study uses GWP 100, which provides more significant results, as the indicator for sensitivity analysis. Fig. 5(a) shows the results for the GWP 100 sensitivity analysis. In typical circumstances, GWP 100 for

Table 4
Life-cycle endpoint impact (Point) for different scenarios using the ReCiPe methodology (functional unit: per ha).

Endpoint	Category	S1		S2		S3		S4	
		Manufacture	Farmland	Manufacture	Farmland	Manufacture	Farmland	Manufacture	Farmland
Ecosystem quality	Natural land transformation	79.75	-	42.54	-	79.76	-	42.54	-
	Terrestrial ecotoxicity	35.93	-	19.16	-	35.93	-	19.16	-
	Freshwater eutrophication	0.08	0.40	0.04	0.21	0.08	0.16	0.04	0.09
	Terrestrial acidification	1.03	-	0.55	-	1.03	-	0.55	-
	Agricultural land occupation	126.66	-	67.55	-	126.66	-	67.55	-
	Freshwater ecotoxicity	0.10	0.83	0.05	0.44	0.1	0.33	0.05	0.18
	Marine ecotoxicity	18.84	0.01	10.05	0.005	18.84	0.004	10.05	0.002
	Climate change, ecosystems	152.96	27.49	83.13	11.41	152.97	27.49	83.13	11.43
	Urban land occupation	1298352.31	-	692454.57	-	1298352.31	-	692454.57	-
	Total	1298767.65	28.72	692677.65	12.07	1298767.66	27.97	692677.65	11.68
Human health	Ionizing radiation	0.05	-	0.03	-	0.05	-	0.03	-
	Human toxicity	567.31	-	302.57	-	567.31	-	302.57	-
	Climate change	192.44	34.58	104.59	14.36	192.45	34.58	104.59	14.37
	Photochemical oxidant formation	1.66	-	0.89	-	1.66	-	0.89	-
	Ozone depletion	0.00914	-	0.00487	-	0.00914	-	0.00487	-
	Particulate matter formation	30.67	-	16.48	-	30.67	-	16.48	-
	Total	911.59	34.58	424.56	14.36	792.15	34.58	424.56	14.37
Resource	fossil depletion	131.82	-	70.31	-	131.82	-	70.31	-
	metal depletion	63.65	-	-	33.95	63.65	-	33.95	-
	Total	195.47	-	104.26	-	195.48	-	104.26	-
Total	1299755.26	63.30	693206.47	26.43	1299755.28	62.55	693206.47	26.06	

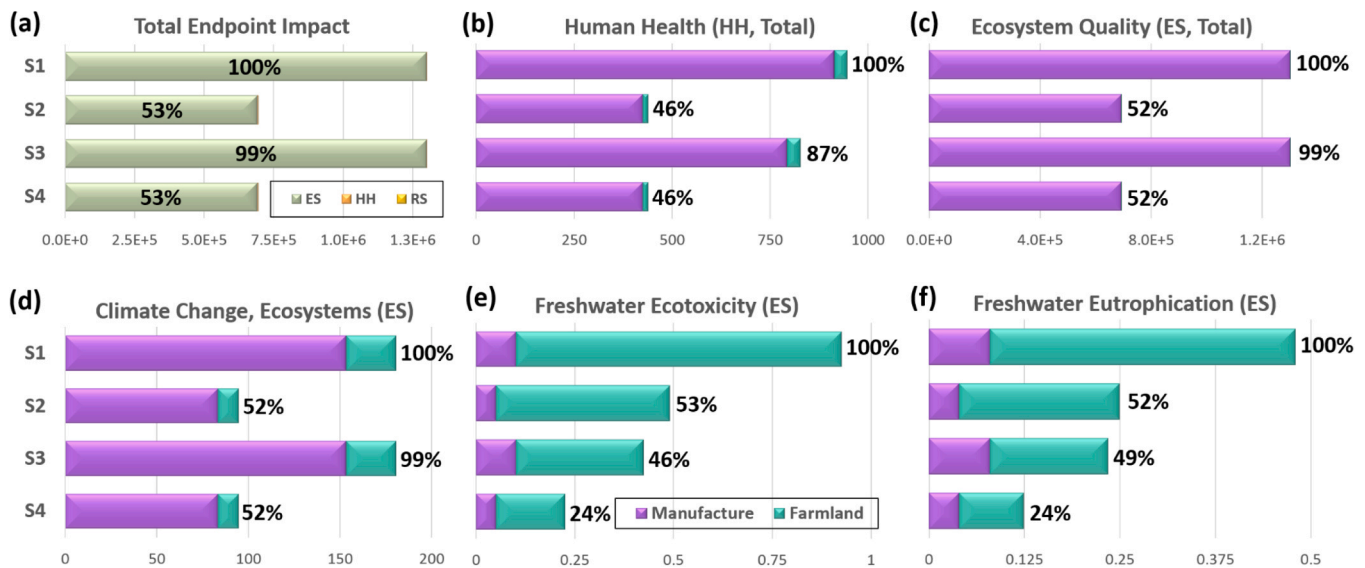


Fig. 4. Endpoint impact assessment (Point) for different scenarios: (a) total endpoint impact, including ecosystem quality (ES), human health (HH), and resource depletion (RS); (b) human health (HH, total); (c) ecosystem quality (ES, total); (d) climate change, ecosystems (ES); (e) freshwater ecotoxicity (ES); (f) freshwater eutrophication (ES).

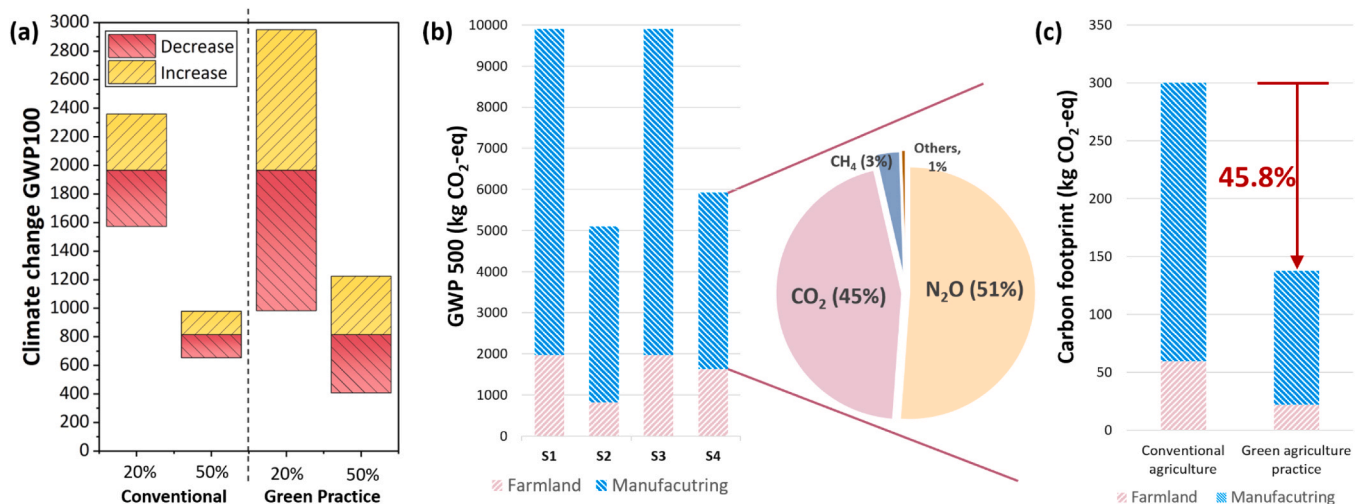


Fig. 5. (a) Sensitivity analysis of GWP 100 for conventional agriculture and green agricultural practices. (b) Emission details of manufacturing phase. (c) Carbon footprint, in terms of kg CO₂-eq per tonne of plum.

conventional agriculture is ~1967 kg CO₂-eq for the farmland phase and ~817 kg CO₂-eq for the rational fertilization and the use of biochar. Increasing fertilizer usage by 20 % raises GWP 100 to ~2369 kg CO₂-eq (an increase of approximately 20 %), while reducing fertilizer usage by 20 % lowers GWP 100 to ~1573 kg CO₂-eq, a 20 % reduction in impact. This result clearly shows that the amount of fertilizer applied is the factor that most significantly influences GWP 100 values. Fertilizer use strongly affects GWP due to the significant emissions associated with the manufacturing phase. As shown in Fig. 3(a), 80 % of GWP 100 is contributed by the manufacturing phase. Therefore, optimizing fertilizer usage could lead to substantial reductions in GWP. In contrast, biochar addition has a smaller impact on GWP, indicating that while it enhances soil quality, its effect on GWP is less pronounced.

This study predominantly focuses on the flow of NPS pollutants during the farmland stage, but emissions from the manufacturing process are also important. Fig. 5(b) shows the contribution of manufacturing emissions to CO₂-eq. The largest proportion is N₂O, which accounts for about 51 % of the total, followed by CO₂ at about

45 %, and CH₄ at 3 %. The remaining substances include volatile organic compounds, chloroform, and nitrogen fluoride. These contribute little to GHG emissions, but their emission sources affect human health and the composition of the ozone layer, thereby influencing global warming. Hussain et al. (2024) showed that volatile organic compounds also significantly impact regional air quality. When they diffuse into the atmosphere, they initiate chemical processes that lead to the production of ground-level ozone, a major component of smog. Ground-level ozone causes respiratory problems, reduces crop yields, and damages habitats (Zulkifli et al., 2022). Bale et al. (2011) reported that even low concentrations of chloroform can cause serious damage to the skin, kidneys, liver, immune system, and nervous system. Fig. 5(c) shows the difference in the carbon footprint for plums cultivated using conventional agriculture versus green agricultural practices, in terms of plum yield. The results show that the production of one tonne of plums using conventional agriculture emits ~300 kg CO₂-eq, whereas using green agricultural practices results in only ~138 kg CO₂-eq, representing a reduction of 45.8 % in GHG emissions.

3.5. Implications for responsible consumption and production

Best management practices (BMPs) including rational fertilization, biochar, and CW are critical for reducing agricultural NPS pollution. For instance, the results of the LCA analysis show that combining the use of biochar with rational fertilization (S2) increases crop yields by ~11 % (see Table 1) and reduces overall environmental endpoint impacts by ~47 % (see Fig. 4(a)). The increase in yield can be attributed to biochar's ability to enhance soil fertility and improve nutrient uptake by crops (as shown in Fig. 2). In this study, the biochar is produced from agricultural residues through pyrolysis, which minimizes additional costs. Moreover, reducing fertilizer use to half the standard amount decreases fertilizer expenses. This combination of cost reduction and an 11 % yield increase demonstrates that the approach is highly economically viable. The study also shows that rational fertilization reduces fertilizer consumption, which lessens environmental damage. Within the farmland phase, GWP100 is estimated to decrease from ~1967 kg CO₂-eq to ~817 kg CO₂-eq, representing a reduction of ~58 %.

The implementation of CWs further improves water quality, reducing the impacts of freshwater and marine eutrophication from the farmland phase by ~50 %. These results demonstrate that the combined use of biochar and CWs mitigates eutrophication and reduces environmental impacts. Vymazal et al. (2021) collated more than 130 research articles on CWs and found that less than 10 % of the experiments were conducted at full scale. This highlights the need for full-scale operations to evaluate and optimize such systems. Despite the environmental benefits associated with the use of biochar and CWs, the results of this study show that CWs are primarily effective in mitigating water eutrophication but have a limited contribution on the reduction of GWP and other environmental impacts. In other words, a portfolio of green practices should be implemented to mitigate the overall environmental impacts of agricultural activities, including nutrient loadings and GWP.

The results of this study demonstrate the urgent need for policy interventions to encourage the adoption of green agricultural practices (Kua et al., 2023; Liu et al., 2023; Prokopy et al., 2019). Garmendia-Lemus et al. (2024) found that social influences and circles significantly shape farmers' intentions to use bio-based fertilizers, underscoring the importance of education in promoting the adoption of biochar use and BMPs. The adoption of nature-based solutions (NbS) also offers a promising pathway toward achieving Clean Water and Sanitation (SDG 6), Responsible Consumption and Production (SDG 12), Climate Action (SDG 13), and Life on Land (SDG 15) (Debele et al., 2023). NbS provide a significant carbon sink and enhance carbon sequestration processes (Sun et al., 2024). Future research should focus on identifying and developing innovative NbS to mitigate agricultural NPS pollution. Additionally, understanding the social, economic, and cultural factors that influence farmers' adoption of sustainable practices is essential to ensure their widespread implementation and maximize the impact of these interventions. NbS approaches, such as green agricultural practices, enable a more sustainable and resilient agricultural system that safeguards the environment, promotes human well-being, and contributes to achieving the SDGs.

4. Conclusions

This study demonstrates that green agricultural practices (including rational fertilization, biochar, and CWs) significantly inhibit NPS pollution and nutrient loadings. The findings indicate that, compared to a conventional agriculture scenario, rational fertilization (a half dosage of fertilizers) combined with biochar reduces total endpoint impacts by ~47 %, including a ~54 % reduction in effects on human health. Biochar alone increases the utilization efficiency of nitrogen (from 57 % to 89 %) and phosphorus (from 9 % to 63 %). CWs alone also achieve a 50 % reduction in freshwater eutrophication and reduce marine eutrophication from ~41.8 kg N-eq to ~20.8 kg N-eq (~50 % reduction), providing significant benefits for aquatic ecosystem quality. Compared

to a conventional agriculture scenario, a combination of rational fertilization and CWs reduces marine eutrophication potential by ~70 % and freshwater eutrophication potential by ~74 %. Sensitivity analyses show that the effect of CW construction on GWP is negligible, while the dosage of fertilizer application directly impacts GWP. In terms of carbon footprint, green agricultural practices (~138 kg CO₂-eq per tonne of plum) reduce GHG emissions by 45.8 % compared to conventional agriculture (~300 kg CO₂-eq per tonne of plum). These results highlight the potential for green practices to mitigate NPS nutrient loadings and environmental effects, supporting the achievement of sustainable agricultural management.

CRedit authorship contribution statement

Markéta Šerešová: Writing – review & editing, Methodology, Data curation. **Yu-Ning Chen:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Shu-Yuan Pan:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Jan Vymazal:** Writing – review & editing, Supervision, Project administration. **Chihhao Fan:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Michal Šeres:** Writing – review & editing, Resources, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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