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Research article

The advantages in crop yields and carbon footprints of maize-soybean relay strip intercropping

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ABSTRACT

Intercropping can improve nutrient utilization, but the mechanisms of greenhouse gas (GHG) emissions, energy use, and carbon footprint in rain-fed cereal-legume intercropping remain unclear. Hence, a two-year field trial was conducted to evaluate cropping systems' productivity, carbon footprint, energy inputs, and outputs. The cropping systems include monocropping maize (M) and soybean (S), maize-soybean relay strip intercropping (IMS), and maize-soybean alternate row relay intercropping (CMS). Results showed that the grain yield of the IMS system (9.1 t ha^{-1}) was three times that of S and resulted from a complementary effect rather than a selection effect. Although the differences in yield between IMS, CMS, and M were insignificant, the land equivalent ratio (LER) of IMS and CMS was higher than one, mainly due to the partial LER of maize. Besides, the economic benefit of IMS was 41.2 % higher than CMS, 48.1 % higher than M, and 119.2 % higher than S, respectively. In IMS, the complementary effect mainly results from the advantages of decreasing direct CO_2 equivalent emissions and indicating CO_2 equivalent emissions, consequently obtaining a lower yield and economic benefit scaled greenhouse gas emissions intensity (GHGI). Furthermore, the net energy output, yield-scaled carbon footprints, yield economic benefit-scaled carbon footprints, and energy output-scaled carbon footprints were 31.4 %, 3.3 %, 25.5 %, and 30.3 % notably lower in IMS than in M, respectively. The complementary effect boosted the advantages in energy productivity, specific energy, energy profitability, and carbon footprint of IMS, but the net energy outputs and energy use efficiency were insignificant between IMS and CMS. The results indicate that the maize-soybean relay strip intercropping provides ways to achieve cleaner production in rain-fed areas.

1. Introduction

Drylands cover 41 % of the world's land area, and dryland crops such as maize, wheat, soybeans, and rapeseed are the main food and economic sources for over 38 % of the world's population (Maestre et al., 2012). Strengthened agricultural production, exemplified by increasing fertilizers input, has increased crop yields per unit area (Lassaletta et al., 2014). However, this production intensification has caused severe environmental issues. Consequently, agricultural systems contribute 10–12 % of total greenhouse gas (GHG) emissions (Derpsch et al., 2014; IPCC, 2014). Since 1970, the extensive use of chemical fertilizers has increased GHG emissions by 35 % (Benbi, 2018; Fan et al., 2005), and more than 40 % of total indirect GHG emissions come from nitrogen fertilizers (Nia et al., 2024), causing severe environmental issues. Carbon footprint (CF; CO_2 emissions per unit of seed yield gain) as an indicator to quantify GHG emissions, which includes direct GHG emissions from crop growth and indirect GHG emissions from agricultural production inputs and field management (Gan et al., 2014; Liu et al., 2016). Therefore, crop cultivation practices (i.e., intercropping) provide potential approaches to increase crop productivity and reduce carbon footprint in agricultural production.

Various methods are practiced to decline carbon footprint in agricultural production, field management (e.g., no-tillage, reduced tillage, and straw mulching) and cropping pattern (e.g., rotation, intercropping,

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and relay intercropping) (Lal et al., 2019; Yadav et al., 2018; Yin et al., 2022). The rice-maize rotation with no-till declined carbon footprint by 39.0 % compared with conventional-till (Lal et al., 2019). Similarly, rice-mustard rotation with no-till and residue retention obtained a 12.7 % lower carbon footprint than the rotation with conventional-till and residue mulch (Yadav et al., 2018). Among those methods, intercropping has a higher multiple cropping index by involving planting two or more crops on the same land, which can increase land output and improve soil quality (Brooker et al., 2015; Chen et al., 2019; Du et al., 2018; Li, et al. 2001, 2014; Wang et al., 2023a). The land equivalent ratio (LER) of maize-soybean and maize-red bean intercropping are 1.27 and 1.30, respectively, suggesting a higher land use efficiency than monocropping (Zhang et al., 2015). The intercropped maize and faba bean yields increased by 43 % and 26 %, respectively, compared with the corresponding monocropping (Li et al., 2007). The yields of maize-soybean intercropping and maize-peanut intercropping were 40 % and 15.5 % higher than mono maize (Wang et al., 2023a). Moreover, researchers confirmed that beet-arugula intercropping can reduce carbon footprint without penalty on yield (Cecilio Filho et al., 2022). Intercropping might be an effective strategy to increase crop productivity while reducing the carbon footprint. However, there are differences in carbon emissions and carbon footprint when different crop species are intercropped. The carbon emissions, water use efficiency based on carbon emissions, carbon footprint of the wheat-maize intercropping system were 18.9 %, 27.2 %, and 27.6 % lower than those of monoculture maize, respectively, while the carbon emission efficiency increased by 39.9 % in semi-arid areas (Yin, et al. 2017, 2022). Besides, maize-soybean intercropping had higher net income and carbon sustainability index compared with maize-peanut intercropping (Wang et al., 2023a). Although intercropping provides a way to reduce environmental costs, the effects of input costs such as seeds, fertilizers, and field management on the energy budget cannot be ignored.

Energy budget and environmental costs are crucial indicators in assessing the sustainability of agricultural production (Hatfield et al., 2017). Various approaches have been conducted in agricultural production, field management (e.g., no-tillage and straw mulching), and cropping systems (e.g., rotation and intercropping) (Lal et al., 2019; Li et al., 2021; Yang et al., 2023; Yin et al., 2022). Li et al. (2021) demonstrated that rice practiced with no tillage obtained 25.0 % higher energy use efficiency than conventional tillage. In rice-maize rotation, the energy consumption is 56.0 % lower in no-till than in conventional-tillage (Lal et al., 2019). Conversely, energy consumption of no-tillage was 36.9 % higher than conventional tillage in maize-wheat intercropping (Yin et al., 2022). Some studies have reported different results in terms of energy efficiency and ecological sustainability analysis. The energy yield ratio and energy sustainability index of monoculture maize were 13.7 % and 21.1 % higher than those of maize-soybean intercropping, respectively. Meanwhile, the environmental load ratio was 7.3 % lower than that of intercropping, primarily due to the high labor input and low energy output in maize-soybean intercropping (Yang et al., 2018). Although monocropping with improved field management obtained higher energy use efficiency and a lower carbon footprint, intercropping achieved higher resource use and land productivity with fewer environmental costs than monocropping (Yin et al., 2022). Besides, energy use is 36.9 % higher in no-tillage than conventional tillage in maize-wheat intercropping (Yin et al., 2022). Additionally, legumes transfer biologically fixed nitrogen to meet cereal nitrogen demand in legume-based intercropping (X. et al., 2004). This reduces nitrogen fertilizer inputs and greenhouse gas emissions in agricultural production (X. et al., 2004; Zhang et al., 2021b). In the current agricultural production scenarios, intercropping provides potential approaches to achieving sustainable agricultural production in the semi-arid area (Chai et al., 2021; Wang, et al. 2023b, 2023c; Zhang et al., 2024b). However, in relay strip intercropping at rainfed areas, how species interactions influence grain yield, energy use, and carbon footprint remains unclear.

Loreau and Hector (2001) reported that interspecific interactions among species are critical in plant production. In biodiversity experiments, net effect (NE), complementary effect (CE), and selection effect (SE) are used to assess interactions between species in the system and their impact on species productivity and resource utilization (Li et al., 2018; Loreau and Hector, 2001; Zhang, et al. 2021). In faba bean-maize intercropping, the CE rather than the SE improved resource use (Li et al., 2018). However, the higher yield of maize-soybean intercropping compared to maize-peanut intercropping is attributed to a stronger selection effect (Wang et al., 2023a). However, the CE and SE in maize-chickpea and maize-soybean intercropping contribute equally to resource use (Li et al., 2018; Zhang et al., 2020a; Zhang, et al. 2021a). In maize-soybean intercropping, nitrogen use mainly resulted from CE rather than SE; conversely, phosphorus utilization mainly resulted from SE rather than CE (Zhang, et al. 2021a). However, in maize-soybean relay strip intercropping, how species interactions (i.e., net effect, complementary effect, selection effect) affected land productivity, energy use, and carbon footprint in rainfed areas remains unclear. Therefore, this study aims to (1) clarify the productivity and carbon footprint characteristics of maize-soybean relay strip intercropping systems; (2) evaluate the impacts of the complementary effect and the selection effect on the productivity, economic benefits, and carbon footprint in the intercropping system. The results will enhance our understanding of how biodiversity affects crop productivity and environmental impact and provide valuable insights for developing high-yield, environmentally friendly, and sustainable production practices.

2. Materials and methods

2.1. Experimental site

The experimental site was located in Renshou Modern Agriculture Grain Park, which is situated in a hilly area in Southwest China. The region has a subtropical monsoon climate and is positioned at 29°60′ N and 104°00′ E. The experiment was conducted during the 2021 to 2022 crop growing seasons, and the long-term experiment has been carried out at the site since 2012 (Chen et al., 2017).

2.2. Experimental design

A single-factor randomized block-designed experiment was conducted with four treatments, including monocropping maize (M), monocropping soybean (S), maize-soybean relay strip intercropping (IMS), and conventional maize-soybean intercropping (CMS). Each plot was repeated three times, making a total of 12 plots. Each plot is 6 m long and 6 m wide, and the plot area is 36 m^2. In IMS, two rows of maize were relay intercropped with two rows of soybeans. In CMS, one row of soybean alternated intercropping with one row of maize (Fig. S1). The planting density of monocropping maize and soybean was 58,500 and 117,000 plants per hectare (ha.), respectively. The IMS and CMS were full additive relay intercropping, and the planting density of intercropped maize and soybean was the same as that of the corresponding monocropping. More details about crop planting are introduced in Fig. S1.

The fertilizers used in the study were urea (N $\geq$ 46 %), superphosphate ($P_2O_5 \geq 12$ %), and potassium chloride ($K_2O \geq 60$ %). As stated above, we implemented a full additive relay strip intercropping system. Consequently, the supply of fertilizers to the component species in intercropping was the same as that in the corresponding monocropping. Nitrogen fertilizer was applied to maize at two different times: 72 kg N ha^{-1} at sowing and 108 kg N ha^{-1} at the tasseling stage. The base fertilizers per hectare of maize were composed of 72 kg N, 105 kg P_2O_5, and 112.5 kg K_2O, and those for soybeans were 60 kg N, 63 kg P_2O_5, and 52.5 kg K_2O. The base fertilizers were placed 10 cm away from the corresponding crop rows.

2.3. Crop yield, land equivalent ratio, system productivity index, and competition

At the mature stage of maize and soybean, a strip of maize and soybean from the middle row of each plot was collected to determine the yield. The land equivalent ratio (LER) is commonly used to assess the productivity and land utilization of intercropping (Mead and Willey, 1980). An LER lower than one indicates that intercropping has low land use efficiency and declines productivity compared to monocropping, and LER greater than one means high land use efficiency and more productive than monocropping. The LER was calculated as follows:

$$LER = pLER_m + pLER_s = \frac{Y_{i\_m}}{Y_{s\_m}} + \frac{Y_{i\_s}}{Y_{s\_s}} \tag{1}$$

Where $pLER_m$ and $pLER_s$ are the partial land equivalent ratio of maize and soybean, Y_{i_m} and Y_{s_m} are the grain yield of intercropping and monocropping maize, Y_{i_s} and Y_{s_s} are the grain yield of intercropping and monocropping soybean.

The system productivity index (SPI) is used to evaluate the productivity of crops in intercropping systems (Lithourgidis et al., 2011). The SPI standardizes the yield of secondary crop by the yield of primary crops, and it is calculated as follows:

$$SPI = \frac{S_m}{S_s} \times Y_s + Y_m \ \left(t\ ha^{-1}\right) \tag{2}$$

Where S_m and S_s are the average grain yield of monocropping maize and soybean, Y_m and Y_s are the grain yield of intercropping maize and soybean. The $\frac{S_m}{S_s} \times Y_s$ is the standardized yield of intercropping soybean.

Aggressivity is used to evaluate the relative competition of the component species in an intercropping system (Lithourgidis et al., 2011), and the calculation is as follows:

$$Aggressivity = \frac{Y_{im}}{Y_m \times p_m} - \frac{Y_{is}}{Y_s \times p_s} \tag{3}$$

Where Y_m and Y_s are the grain yield of monocropping maize and soybean, Y_{im} and Y_{is} are the grain yield of intercropping maize and soybean. p_m and p_s are the land-occupied ratio of maize and soybean in intercropping (0.5 and 0.5).

2.4. Economic benefit

Economic benefit analysis is used to evaluate the economic benefit of crop kernel yield, which was calculated as follows:

$$Eeconomic\ benefit = \sum Yield_i \times price_i \ \left(CNY\ ha^{-1}\right) \tag{4}$$

Where $Yield_i$ and $price_i$ are the grain yield and the market prices of species i, and i is maize or soybean. The economic benefits were calculated based on the local prices (Chinese Yuan, CNY) of maize (2.4 CNY kg^{-1}) and soybeans (6.0 CNY kg^{-1}) in Chengdu, China (https://www.ymt.com).

The net economic benefit is defined as the difference between the economic benefit of crops and the net input, which was calculated as follows:

$$Net\ Eeconomic\ benefit = \sum \left(Eeconomic\ benefit_i - Net\ costs_i\right) \ \left(CNY\ ha^{-1}\right) \tag{5}$$

Where $Eeconomic\ benefit_i$ and $Net\ costs_i$ are the economic benefits of crops, such as maize or soybeans. The agriculture costs, e.g., seeds, fertilizers, diesel, and labor, are calculated based on the corresponding current prices (Table S1). The net cost is the sum of the agriculture costs.

2.5. Energy budget

The total energy input (EI) comprises the combined energy inputs of seeds, fertilizer, plastic film, labor, irrigation, fuel, pesticides, etc (Yin et al., 2022). Energy output (EO) is the sum of grain yield, crop straw, and root energy output. Then, the net energy output (NEO) is the difference between EO and EI. The calculation of EI, EO, and NEO were as follows (Yin et al., 2022):

$$EI = \sum_{i=1}^{n} \left(EI_1 + EI_2 + \cdots + EI_i\right) \ \left(\text{GJ ha}^{-1}\right) \tag{6}$$

$$EO = (G \times EC) + (S \times EC) + (R \times EC) \ \left(\text{GJ ha}^{-1}\right) \tag{7}$$

$$NEO = EO - EI \ \left(\text{GJ ha}^{-1}\right) \tag{8}$$

Where EI is the sum of the amount of each input multiplied by the energy equivalence coefficient, EI_1, EI_2, … EI_n is the energy input of different materials of production during agricultural production. EO is the sum of grain yield (G), straw (S), and root biomass (R) multiplied by the energy equivalence coefficient, EC is the energy equivalence coefficient (MJ $unit^{-1}$), which is listed in Table S2. NEO is the net energy output.

Energy use efficiency (EUE) evaluates how much energy is obtained per MJ of energy consumed per hectare of agricultural production (Kaab et al., 2019). A higher value indicates higher energy use efficiency. Energy productivity (EP) is defined as kilograms of output obtained per MJ of energy input. The specific energy index (SEI) is the ratio of energy input to output, and a higher index means more energy is wasted. Lastly, energy profitability (PE) is the ratio of net energy output to energy input. The calculation of EUE, EP, SEI, and PE were as follows (Kaab et al., 2019):

$$EUE = \frac{EO}{EI} \tag{9}$$

$$EP = \frac{Y}{EI} \ \left(kg\ MJ^{-1}\right) \tag{10}$$

$$SEI = \frac{EI}{Y} \ \left(MJ\ kg^{-1}\right) \tag{11}$$

$$PE = \frac{NEO}{EI} \tag{12}$$

Where EUE is the energy use efficiency, EI is the energy input, and EO is the energy output. EP is the energy productivity, and Y is the crop grain yield. SEI is the specific energy index, PE is the energy profitability, and NEO is the net energy output.

2.6. Soil greenhouse gas emissions

The 0.5m × 0.5m × 0.5m static boxes were used to collect greenhouse gases (GHG) (Luo and Zhou, 2006). The static boxes were placed at the center of interspecific rows in IMS and CMS and at the wide monocropping rows (Fig. S1). Samples were collected at the maize tasseling and silking stages, and sampling was done on the 1st, 3rd, 5th, 8th, and 13th days after soybean sowing. Then, sampling once a week before maize harvest. After the maize harvest, samples were collected at the R2, R4, R6, and R8 stages of soybean (Fehr et al., 1971) within the period of 9:00–11:00 in the morning. The GHG gases were collected using a syringe at 0, 10, 20, and 30 min after sealing the box. A 150 mL sample was collected each time and then injected into a 200 mL gas sampling bag. Finally, the GHG concentration was measured using a Shimadzu gas chromatograph (SHIMADZU-GC2010-PLUS). The GHG emissions fluxes and cumulative emissions were calculated as follows (Rolston, 1986; Yin et al., 2022):

$$F = \rho \times h \times \frac{dc}{dt} \times \frac{273}{273 + T} \ (\mathrm{mg\ m^{-2}}\ h^{-1}) \tag{13}$$

$$CE_{GHG} = \sum \left[\left(\frac{F_{i+1} + F_i}{2} \times (t_{i+1} - t_i) \right) \right] \times 24 \times \frac{1}{100} \ (\mathrm{kg\ CO_2\text{-}eq\ ha^{-1}}) \tag{14}$$

Where F is the flux of greenhouse gas (CO_2, CH_4, or N_2O), ρ is the density of greenhouse gases at standard atmospheric pressure. h is the height of the box, $\frac{dc}{dt}$ is the rate of increase of greenhouse gas concentration in box per unit time. The temperature kelvin coefficient is 273. T is the average temperature (°C) inside the box. CE_{GHG} is the cumulative emissions of greenhouse emissions. The F_i and F_{i+1} are the fluxes at the time t_i and t_{i+1}

Direct CO_2 equivalent emissions (DE) are the sum of cumulative emissions of CO_2, CO_2 scaled N_2O and CH_4 emissions (Yin et al., 2022). The global warming potential of N_2O and CH_4 are 298 and 28 times that of CO_2 (Chai et al., 2021; IPCC, 2014). The DE was calculated as follows (Yin et al., 2022):

$$DE = CE_{N_2O} \times 298 + CE_{CH_4} \times 28 \ (\mathrm{kg\ CO_2\text{-}eq\ ha^{-1}}) \tag{15}$$

Where DE is the direct CO_2 equivalent emissions, the CE_{N_2O} and CE_{CH_4} are the cumulative emissions of N_2O and CH_4

The indirect CO_2 equivalent emissions (IE, kg CO_2-eq ha^{-1}) are defined as the total CO_2 equivalent emissions of each component, including seeds (maize and soybean), fertilizers (N, P, and K), human labor, diesel, and Herbicide (Table S3) (Yin et al., 2022). The IE was calculated as follows:

$$IE = \sum_{i=1}^{n} (ICE_1 + ICE_2 + \cdots + ICE_n) \ (\mathrm{kg\ CO_2\text{-}eq\ ha^{-1}}) \tag{16}$$

Where IE is the soil indirect CO_2 emissions, ICE_1, ICE_2, …ICE_n are the CO_2 equivalent emissions of each component

2.7. Carbon footprint

Carbon footprint (CF) is defined as the total GHG emissions associated with food production in CO_2 equivalent, including greenhouse gas emissions from agricultural inputs (seeds, nitrogen, phosphorus, and potassium fertilizers, fuel for irrigation, and indirect emissions from labor) (Gan et al., 2012; Wang et al., 2023a; Yang et al., 2014), as well as emissions from the manufacturing, packaging, and transportation of agricultural inputs, and direct greenhouse gas emissions from farmland (China Products Carbon Footprint Factors Database) (Fig. S2). Then, the grain yield scaled CF (CF_Y), economic benefit scaled CF (CF_{EB}), net economic benefit scaled CF (CF_{NEB}), and energy output scaled CF (CF_{EO}) were calculated as follows (Yang et al., 2014; Yin et al., 2022):

$$CF = IE + DE + \Delta SOCS \ (\mathrm{Mg\ CO_2\text{-}eq\ ha^{-1}}) \tag{17}$$

$$\Delta SOCS = \frac{SOC_{S\_i} - SOC_0}{Y} \ (\mathrm{Mg\ C\ ha^{-1}\ yr^{-1}}) \tag{18}$$

$$SOC_S = \mathrm{BD} \times \mathrm{SOC} \times 20 \times 100 \ (\mathrm{Mg\ C\ ha^{-1}}) \tag{19}$$

$$CF_Y = \frac{CF}{Yield} \ (\mathrm{kg\ CO_2\text{-}eq\ ha^{-1}}) \tag{20}$$

$$CF_{EB} = \frac{CF}{Economic\ benefit} \ (\mathrm{kg\ CO_2\text{-}eq\ CNY^{-1}}) \tag{21}$$

$$CF_{NEB} = \frac{CF}{Net\ economic\ benefit} \ (\mathrm{kg\ CO_2\text{-}eq\ CNY^{-1}}) \tag{22}$$

$$CF_{EO} = \frac{CF}{EO} \ (\mathrm{kg\ CO_2\text{-}eq\ KJ^{-1}}) \tag{23}$$

Where CF is carbon footprints, IE, is indirect CO_2 equivalent emissions, DE, direct CO_2 equivalent emissions, $\Delta SOCS$ is soil organic carbon stock rate, SOC_S is soil organic carbon storage. SOC_{s_i} and SOC_0 are soil organic carbon storage after crop harvest and before crop sowing. Y is years of experiment conducted. SOC_S, BD, and SOC are soil organic carbon storage, soil bulk density, and soil organic carbon content of top soil layer (0 20 cm). CF_Y is the grain yield scaled carbon footprint, and yield is the crop grain yield. CF_B is an economic benefit scaled carbon footprint. The economic benefit is the economic benefit of crop grain yield. CF_{NEB} is net economic benefit scaled carbon footprint. The net economic benefit is the difference between the economic benefit of crops and the net input. CF_{EO} is energy scaled carbon footprint. EO is energy output

2.8. Global warming potential and greenhouse gas emissions intensity

Global warming potential (GWP) is a critical indicator for quantifying the impact of greenhouse gas emissions on the ecosystem (IPCC, 2014). On the basis of GWP, the yield, economic benefit, and land equivalent ratio scaled greenhouse gas emissions intensity (GHGI) can be used to evaluate the environmental impacts of greenhouse gas emissions (Wang et al., 2022). In this study, the GWP was the same as direct CO_2 equivalent emissions, which were calculated as formula 15. The yield, economic benefit, and land equivalent ratio scaled GHGI were calculated as follows (IPCC, 2014; Wang et al., 2022):

$$GHGI_Y = \frac{GWP}{Yield} \ (\mathrm{kg\ CO_2\text{-}eq\ kg^{-1}}) \tag{24}$$

$$GHGI_B = \frac{GWP}{Economic\ benefit} \ (\mathrm{kg\ CO_2\text{-}eq\ CNY^{-1}}) \tag{25}$$

$$GHGI_{LER} = \frac{GWP}{LER} \ (\mathrm{kg\ CO_2\text{-}eq\ ha^{-1}}) \tag{26}$$

Where GWP is global warming potential. $GHGI_Y$, $GHGI_B$, and $GHGI_{LER}$ are crop grain, economic benefit, and land equivalent ratio (LER) scaled greenhouse gas emissions intensities. A low value of GHGI suggests low greenhouse gas emissions per unit outcome.

2.9. Complementary effect, selection effect, and net effect

The biodiversity experiment used the complementary, selection, and net effects to quantify the advantage of grain yield and resource use (Li et al., 2018; Loreau and Hector, 2001; Xing et al., 2023). In this study, the NE, CE, and SE were calculated based on the grain yield and environmental factors in intercropping as follows (Fig. S3):

$$NE_{ij} = CE_{ij} + SE_{ij} \tag{27}$$

$$CE_{ij} = \left(\sum RC_{ij} - 1 \right) \times \overline{M}_{ij} \tag{28}$$

$$SE_{ij} = 2 \times cov(\Delta RC_{ij}, \mathrm{M}_{ij}) \tag{29}$$

$$RC_{ij} = \frac{I_{ij}}{M_{ij}} \tag{30}$$

$$\Delta RC_{ij} = RC_{ij}\text{-}RC_{ij}^{0} \tag{31}$$

Where CE_{ij}, SE_{ij}, and NE_{ij} are complementary, selection, and net effect of the i-th indicator of species j. The i is the indicator including grain yield, DE, TE, EB, NEB, $GHGI_Y$, $GHGI_B$, NEO, EUE, EP, SEI, PE, CF, CF_Y, CF_{EB}, CF_{NEB}, and CF_{EO}. RC_{ij} is the relative change of the i-th indicator, and species j includes maize and soybean. I_{ij} and M_{ij} are the i-th indicator value of species j in intercropping and monocropping. ΔRC_{ij}, the i-th indicator relative change of species j, RY_{ij}^{0}, the i-th indicator expected change of indicator of species j. $\overline{M}_{ij}$, mean of the i-th indicator of species j

in monocropping.

A positive CE_{ij} denotes that, on average, the i-th indicator of species j in intercropping is higher than that of monocropping. On the contrary, a negative CE_{ij} indicates that intercropping is not beneficial to the increase of the i-th indicator. Positive SE_{ij} suggests that the rise in the i-th indicator comes from dominant crops (maize). At the same time, negative SE_{ij} indicates that the increase of the i-th indicator in intercropping is inferior to that of monocropping.

According to the definition of environmental indicators such as EB, NEB, NEO, EUE, EP, SEI, and PE, high values imply more efficient use of resources and low environmental costs. Then, a positive CE of these environmental indicators denotes that, on average, the resource use of species in intercropping is higher than that of monocropping, leading to low environmental costs. Conversely, a negative CE indicates intercropping does not benefit resource use and may enhance environmental costs. A positive SE indicates that the advantage of resource use and lower environmental costs comes from dominant crops (maize); in contrast, a negative SE indicates lower resource use or higher environmental costs in intercropping compared to monocropping.

On the contrary, according to the definition of environmental factors (DE, TE, $GHGI_Y$, $GHGI_B$, CF, CF_Y, CF_{EB}, CF_{NEB}, and CF_{EO}), great values denote less efficient use of resources and high environmental costs. A positive CE of these environmental factors implies that, on average, species in intercropping use fewer resources compared to monocropping, resulting in higher environmental costs. On the other hand, a negative CE indicates that intercropping benefits resource use and reduces environmental costs. A positive SE suggests that the drawbacks of resource use and high environmental costs are associated with dominant crops (maize); in contrast, a negative SE indicates that intercropping has higher resource use or lower environmental costs compared to monocropping.

2.10. Statistical analysis

The one-way ANOVA (tukey, $p < 0.05$) was performed and plot with the GraphPad Prism 9.0 (GraphPad Prism Co., MA, USA). The R software (v. 4.3.2) was employed for data analysis and plot. The Mantel test was visualized with the *linkET* package in R (R version 4.3.2) (Huang, 2021).

3. Results

3.1. Crop productivity and economic benefits of intercropping

The system yield (average of two years) peaked in IMS (9.1 t ha^{-1}), marking 8.8 % and 14.0 % increase compared to M and CMS. Additionally, the yield of the IMS system was three times that of S (Fig. 1A and B). On average, the net effect of IMS (3.8 ± 0.6 Mg ha^{-1}) resulted primarily from the complementary effect (3.5 ± 0.6 Mg ha^{-1}) rather than the selection effect (0.3 ± 0.1 Mg ha^{-1}) (Fig. 2). In contrast, the net effect of CMS (2.7 ± 0.1 Mg ha^{-1}) resulted primarily from the selection effect (2.0 ± 0.1 Mg ha^{-1}) rather than the complementary effect (0.6 ± 0.2 Mg ha^{-1}).

The economic benefit peaked in IMS (28,443.6 CNY ha^{-1}), showing a notable increase of 42.1 %, 35.5 %, and 110.3 % compared to M, CMS, and S, respectively (Fig. 1C and D). There was no significant difference between the economic benefit of S and M due to the higher market price of soybeans compared to maize (Fig. 1C and D). The IMS system (20573.8 CNY ha^{-1}) achieved the highest net economic benefit, showing a significant increase of 48.0 %, 79.5 %, and 111.6 % compared to M, CMS, and S, respectively (Fig. 1E and F). The economic benefit of IMS exceeded that of CMS due to lower soybean yield and economic benefits in CMS. Generally, the economic benefit of IMS benefits more from the complementary effect, but that of CMS resulted from more robust selection effect (Table 3).

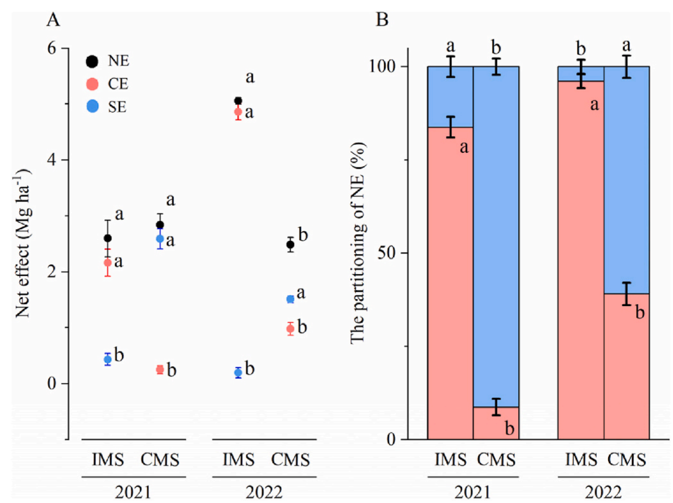

Fig. 2. Effect of cropping systems on net effect, complementary effect, selection effect, and the partitioning of net effect. For an explanation of abbreviations IMS and CMS, please refer to Fig. 1. NE, net effect, CE, complementary effect, SE, selection effect. Values are mean ± standard error. Different lowercase letters signify significant differences among cropping systems of the same item in each crop growing season.

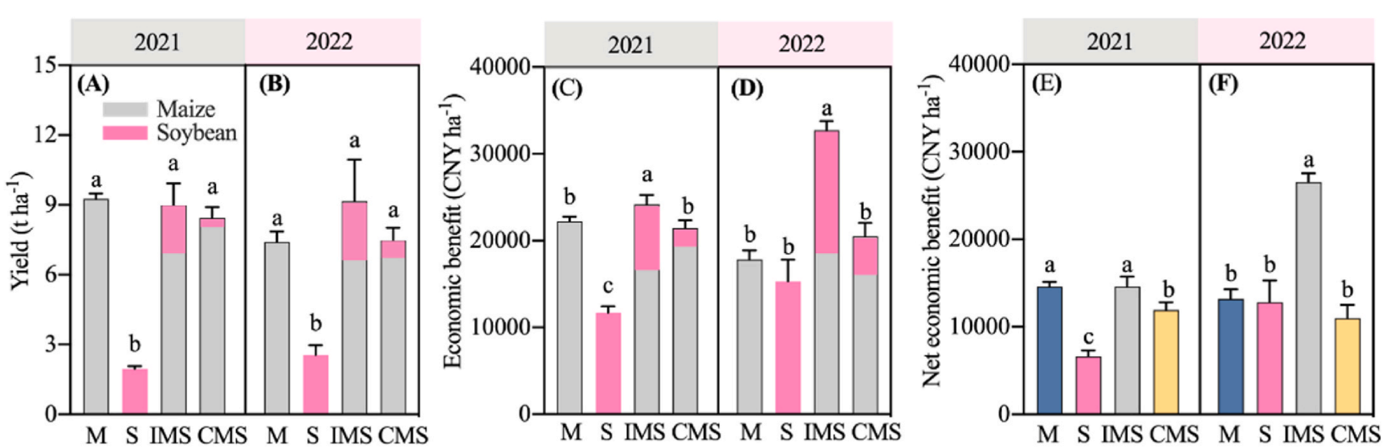

Fig. 1. Effect of cropping systems on grain yield and economic benefit. M, monocropping maize, S, monocropping soybean, IMS, maize-soybean relay strip intercropping, CMS, conventional maize-soybean intercropping. Values are mean ± standard error. Different lowercase letters signify significant differences among cropping systems in each crop growing season.

Overall, the land equivalent ratios (LER) for IMS and CMS were 1.8 and 1.1, respectively. Although both IMS and CMS obtained yield advantages, IMS had more significant yield advantages (Fig. 3A). On average, the partial LER of maize in IMS and CMS was higher than 0.5, suggesting that maize had yield and land use advantages compared to M (Fig. 3A). The partial LER of soybean in IMS was greater than 0.5, while the partial LER for CMS was lower than 0.5, suggesting that soybeans had yield and land use disadvantages in CMS compared to S (Fig. 3A). Besides, the system productivity index (SPI) of IMS was 48.3 % notably greater than that of CMS. This was due to a 2.5 times greater standardized soybean grain yield in IMS than in CMS (Fig. 3B). The IMS had an aggressivity value less than one, while the CMS had a value higher than one. This suggests that the dominant crop (maize) in IMS did not have a competitive inhibitory effect on soybeans. However, soybeans were inhibited by maize competition in CMS (Fig. 3C).

3.2. *Effects of cropping systems on greenhouse gas emissions GWP, $GHGI_Y$, and $GHGI_B$*

The N_2O emission flux showed a significant peak after applying nitrogen fertilizer and topdressing (Fig. S4A and S4B). Over the two crop growing seasons, the peak emission flux was highest in CMS, followed by M, IMS, and S. The cumulative N_2O emissions were peaked in CMS (4.2 kg ha^{-1}) and lowest in S (2.3 kg ha^{-1}). Additionally, IMS showed a notable reduction of 20.7 % and 25.5 % compared with M and CMS (Fig. S4C and S4D). After applying nitrogen fertilizer, the CO_2 emission fluxes increased. Throughout the two crop growing seasons, there were multiple emission peaks in soil CO_2 emission fluxes (Fig. S5A and S5B). The cumulative CO_2 emissions were highest in CMS (11,073.3 kg ha^{-1}) and lowest in IMS. IMS showed a significant decline of 29.5 %, 14.2 %, and 29.9 % compared to M, S, and CMS (Fig. S5C and S5D). Most CH_4 emission fluxes were negative, and the cumulative CH_4 emissions were also negative (Fig. S6A and S6B). The cumulative emissions of CH_4 in IMS were significantly reduced by 71.6 %, 89.4 %, and 93.9 % compared with M, S, and CMS (Fig. S6C and S6D).

The GWP (two-year average) of IMS was notably lower by 28.2 % and 27.6 % compared to M and CMS, respectively (Fig. 4A and B). Although the GWP of IMS increased by 8.0 % compared with S, the difference was insignificant. Results of the land equivalent ratio scaled GHGI ($GHGI_{LER}$) suggest that the CO_2 equivalent greenhouse gas emissions of IMS were 2.1 times lower than CMS (Fig. 3D). In other words, IMS had higher land use efficiency and lower environmental costs than CMS. The $GHGI_Y$ peaked in S (3.3 kg CO_2-eq kg^{-1}) due to low soybean yield and high greenhouse gas emissions. The $GHGI_Y$ of IMS was 34.9 %, 76.8 %, and 36.1 % lower than that of M, S, and CMS (Fig. 4C and D). Additionally, the $GHGI_B$ of IMS (0.2 kg CO_2-eq CNY^{-1}) was significantly lower than M, S, and CMS by 50.7 %, 56.0 %, and 46.4 %, respectively (Fig. 4E and F).

Additionally, the complementary use of resources reduced DE_{CO2} and TE_{CO2} and increased EB and NEB, resulting in $GHGI_Y$ and $GHGI_B$ values that were 91.7 and 67.2 times lower in IMS than in CMS, respectively (Table 3). The selection effect had less impact on CO_2 emissions than the complementary effect. The interspecific competition was more beneficial for maize than for soybeans in terms of grain yield,

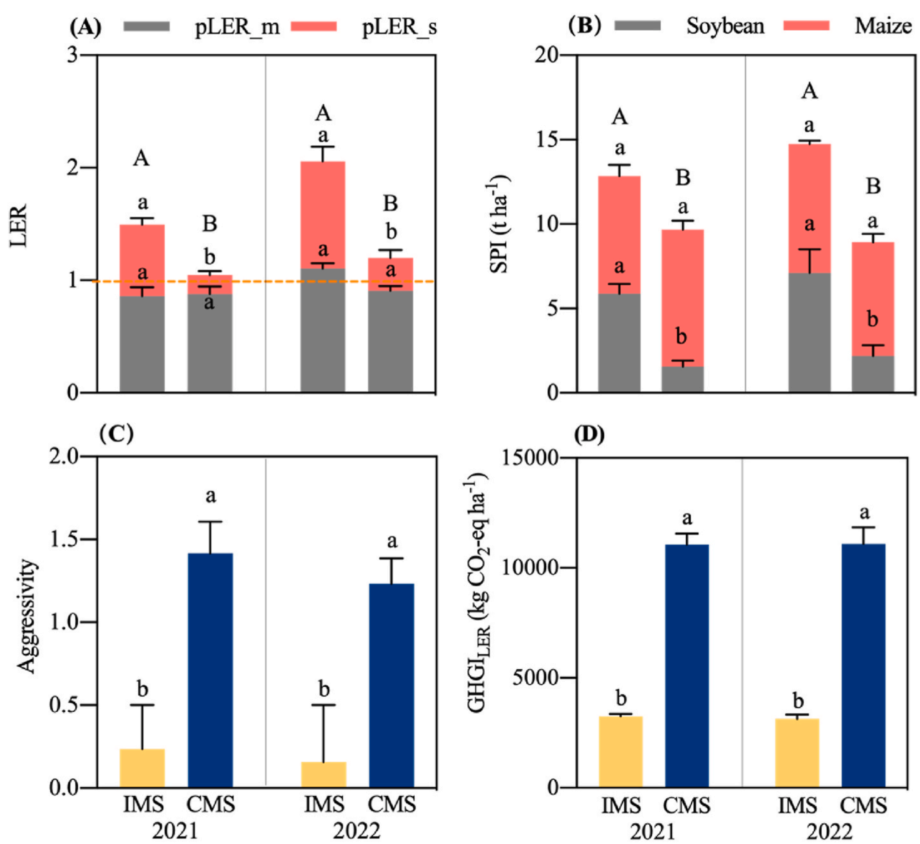

Fig. 3. Effect of cropping systems on land equivalent ratio, system productivity index, aggressivity, and land equivalent ratio scaled greenhouse gas emission intensity. For an explanation of abbreviations IMS and CMS, please refer to Fig. 1. LER, land equivalent ratio of relay strip intercropping system. pLER_m and pLER_s, partial land equivalent ratio of relay intercropped maize and soybean. SPI, the system productivity index that standardized the yield of soybean in terms of maize. Aggressivity, the relative competitive ability of maize to soybean. In intercropping, a value of aggressivity lower than one denotes a weaker competitive ability in maize compared to soybean. $GHGI_{LER}$, land equivalent ratio scaled greenhouse gas emission intensity. A higher value of $GHGI_{LER}$ indicates greater environmental costs associated with the intercropping system. Values are mean ± standard error. Different lowercase letters signify significant differences among cropping systems of the same item in each crop growing season.

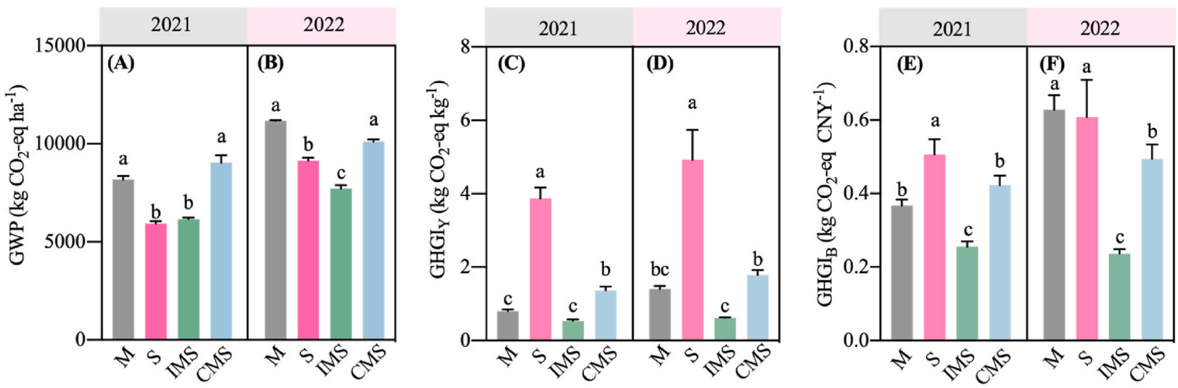

Fig. 4. Effect of different cropping systems on global warming potential. For an explanation of abbreviations M, S, IMS and CMS, please refer to Fig. 1. The black arrows represent fertilization and irrigation. GWP, global warming potential. $GHGI_Y$, grain yield scaled greenhouse gas emission intensity. $GHGI_B$, economic benefit scaled greenhouse gas emission intensity. A higher value of GHGI indicates greater environmental costs associated with the cropping system. Values are mean ± standard error. Different lowercase letters signify significant differences among cropping systems in each crop growing season.

EB, and NEB in CMS, resulting in higher $GHGI_Y$ and $GHGI_B$. Therefore, IMS achieved lower CO_2 equivalent emissions, higher economic benefits, and lower GHGI than CMS (Table 3).

3.3. Effects of cropping systems on energy budget

The energy input (EI) of IMS (mean of two years, 22.9 GJ ha^{-1}) increased by 32.4 % and 192.7 % compared to M and S, respectively (Table 1). The EI of IMS and CMS were equivalent. Because of that, the maize and soybean densities of the two intercropping systems were the same as the corresponding monocropping, and the amount of fertilizer per plant of the same crop was the same. Finally, the seed and fertilizer inputs of IMS and CMS were higher than those of M and S. Chemical fertilizers contributed the most to energy input, accounting for 61.2–76.2 % of the total energy input, with nitrogen fertilizer contributing 47.5–63.3 % (Fig. 5). Following nitrogen fertilizer, pesticides, and phosphate fertilizers accounted for 14.5–28.2 % and 6.7–9.4 % of the total input, respectively. Besides, the total energy budget of IMS and CMS was lower than the total energy budget of the component species.

The energy output (EO) of IMS (388.3 GJ ha^{-1}) increased notably by 31.4 % and 81.2 % compared to M and S, respectively (Table 1). The difference in EO between IMS and CMS was insignificant (Table 1). Finally, the net energy output (NEO) peaked in IMS (365.3 GJ ha^{-1}), increasing by 31.4 %, 77.0 %, and 4.5 % compared to M, S, and CMS (Table 1). Monocropping soybean had the highest energy use efficiency (EUE) at 27.3 (Table 1). The EUE of IMS was 0.7 % and 38 % lower than that of M and S, while 4.4 % higher than that of CMS, respectively. However, there was no significant difference between IMS, M, and CMS (Table 1). The energy productivity (EP) of IMS (0.4 kg MJ^{-1}) was 17.7 % lower than that of M, while it was 14.3 % and 37.9 % higher than CMS and S, respectively. The specific energy index (SEI) of IMS was 2.0, showing a 40.3 % increase compared to M and a 2.5 % and 7.5 % decrease compared to CMS and S, respectively (Table 1). The energy profitability (PE) of IMS and CMS was reduced by 0.7 % and 5.2 % compared to M, while S increased by 64.2 % compared to M.

Results of the net effect, complementary effect, and selection effect suggested that the net energy output and energy use efficiency were independent in intercropping systems (Table 4). However, the net effect of energy productivity, specific energy index, and energy profitability resulted from the complementary effect rather than the selection effect. The IMS achieved a 58.2 % higher net effect of energy productivity and a significantly lower net effect of specific energy index by 294.4 % than that of CMS. Besides, the net effect of energy profitability was more significant in IMS than in CMS due to a high complementary effect (Table 4).

3.4. Effects of cropping systems on soil CO_2 equivalent emissions and carbon footprint

On average, IMS (1806.8 kg CO_2-eq ha^{-1}) showed a significant increase of 32.7 % in indirect CO_2 equivalent emissions (IE) compared to M, while the difference between IMS and CMS was insignificant (Table 2). The IE of S was significantly reduced by 50.1 % compared to M. The IMS (917.4 kg CO_2-eq ha^{-1}) exhibited a significant decline in direct CO_2 equivalent emissions (DE_{CO2}) by 18.2 % and 8.2 % compared to M and CMS, respectively. Regarding monocropping, the DE_{CO2} declined by 52.7 % in soybean compared to maize (Table 2). The total CO_2 emissions of IMS (2724.7 kg CO_2-eq ha^{-1}) were significantly reduced by 2.9 % compared with CMS.

The carbon footprint (CF), grain yield scaled carbon footprint (CF_Y), economic benefit scaled carbon footprint (CF_B), net economic benefit scaled carbon footprint (CF_{NEB}), energy output scaled carbon footprint (CF_{EO}) of IMS were 15.7 %, 28.0 %, 41.5 %, 45.9 %, and 37.9 % lower than those of M, and these were 18.1 %, 32.2 %, 38.9 %, 48.9 %, and

Table 1
Energy input, output, and energy indices in different cropping systems.

Year	CS	EI (GJ ha^{-1})	EO (GJ ha^{-1})	NEO (GJ ha^{-1})	EUE	EP (kg MJ^{-1})	SEI (MJ kg^{-1})	PE
2021	M	17.42b	333.25 ± 6.94 b	315.83 ± 6.94 b	19.10 ± 0.41 b	0.51 ± 0.01 a	1.91 ± 0.05 c	18.12 ± 0.41 b
	S	7.65 c	204.95 ± 2.02 b	197.29 ± 2.02 b	26.81 ± 0.32 a	0.32 ± 0.01 b	3.91 ± 0.20 a	25.81 ± 0.32 a
	IMS	23.13 a	404.48 ± 36.95 a	381.34 ± 35.95 a	17.52 ± 1.61 b	0.41 ± 0.04 ab	2.63 ± 0.30 b	16.52 ± 1.61 b
	CMS	22.99 a	414.15 ± 17.71 a	391.16 ± 17.72 a	18.03 ± 0.80 b	0.43 ± 0.02 b	2.72 ± 0.20 b	17.01 ± 0.82 b
2022	M	17.23 b	257.60 ± 34.59 b	240.37 ± 34.59 b	14.90 ± 2.00 bc	0.41 ± 0.03 a	0.92 ± 0.02 b	13.90 ± 2.02 bc
	S	74.06 c	223.58 ± 9.41 b	215.56 ± 9.41 b	27.93 ± 1.21 a	0.30 ± 0.05 b	0.31 ± 0.01 c	26.91 ± 1.21 a
	IMS	22.73 a	372.04 ± 15.43 a	349.31 ± 15.42 a	16.41 ± 0.71 b	0.41 ± 0.08 ab	1.32 ± 0.10 a	15.42 ± 0.72 b
	CMS	22.96 a	330.83 ± 13.84 a	307.88 ± 13.83 a	14.42 ± 0.62 c	0.32 ± 0.02 b	1.33 ± 0.06 a	13.41 ± 0.61 c

Note: CS, cropping system, M, monocropping maize, S, monocropping soybean, IMS, maize-soybean relay intercropping, CMS, conventional maize-soybean intercropping. EI, energy input, EO, energy output, NEO, net energy output, EUE, energy use efficiency, EP, energy productivity, SEI, specific energy index, PE, energy profitability. Values are mean ± standard error. Different lowercase letters signify significant differences among cropping systems in each crop growing season.

Table 2
Indirect CO_2 emissions, direct CO_2 emissions, and carbon footprint in different cropping systems.

Year	CS	IE_{CO2}	DE_{CO2}	TE_{CO2}	CF	CF_Y	CF_{EB}	CF_{NEB}	CF_{EO}
		(Mg CO_2-eq ha^{-1})				(kg CO_2-eq ha^{-1})	(kg CO_2-eq CNY^{-1})	(kg CO_2-eq CNY^{-1})	(kg CO_2-eq KJ^{-1})
2021	M	1.36b	1.14 ± 0.05 ab	2.50 ± 0.05c	5.49 ± 0.09b	0.59 ± 0.02b	0.25 ± 0.01a	0.38 ± 0.02b	16.48 ± 0.14a
	S	0.68c	0.64 ± 0.02c	1.32 ± 0.02d	3.59 ± 0.08c	1.84 ± 0.10a	0.31 ± 0.02a	0.54 ± 0.05a	17.51 ± 0.35a
	IMS	1.81a	0.96 ± 0.02b	2.77 ± 0.02b	5.89 ± 0.15a	0.66 ± 0.06b	0.24 ± 0.02a	0.41 ± 0.04 ab	14.64 ± 1.14a
	CMS	1.81a	1.24 ± 0.12a	3.05 ± 0.12a	6.09 ± 0.06a	0.72 ± 0.04b	0.28 ± 0.01a	0.51 ± 0.04 ab	14.72 ± 0.55a
2022	M	1.36b	1.11 ± 0.04a	2.47 ± 0.04b	5.79 ± 0.14a	0.78 ± 0.06b	0.33 ± 0.03a	0.57 ± 0.07a	22.76 ± 3.35a
	S	0.68c	0.42 ± 0.04c	1.10 ± 0.04c	4.38 ± 0.07b	1.74 ± 0.27a	0.29 ± 0.05a	0.45 ± 0.10a	19.61 ± 1.07 ab
	IMS	1.81a	0.87 ± 0.02b	2.68 ± 0.02a	5.96 ± 0.15a	0.67 ± 0.15b	0.18 ± 0.01b	0.26 ± 0.02b	16.06 ± 1.02b
	CMS	1.81a	0.76 ± 0.10b	2.57 ± 0.10 ab	5.92 ± 0.11a	0.80 ± 0.07b	0.29 ± 0.02a	0.54 ± 0.08a	17.90 ± 0.57b

Note: M, monocropping maize, S, monocropping soybean, IMS, maize-soybean relay intercropping, CMS, conventional maize-soybean intercropping. IE_{CO2}, indirect CO_2 equivalent emissions, DE_{CO2}, direct CO_2 equivalent emissions, TE_{CO2}, total CO_2 equivalent emissions, CF, carbon footprint, CF_Y: grain yield scaled carbon footprint, CF_{EB}: economic benefit scaled carbon footprint, CF_{NEB}: net economic benefit scaled carbon footprint, CF_{EO}: energy output scaled carbon footprint. Values are mean ± standard error. Different lowercase letters signify significant differences among cropping systems in each crop growing season.

Table 3
Effects of biodiversity on CO_2 emission and economic benefit in intercropping systems.

Year	Term	CS	DE_{CO2}	TE_{CO2}	EB	NEB	$GHGI_Y$	$GHGI_B$
			(Mg CO_2-eq ha^{-1})		(Thousand CNY ha^{-1})		(kg CO_2-eq kg^{-1})	(kg CO_2-eq CNY^{-1})
2021	CE	IMS	−0.90 ± 0.06 b	−0.10 ± 0.06 b	6.55 ± 0.84 a	2.54 ± 0.85 a	0.51 ± 0.03 b	0.11 ± 0.01 b
		CMS	1.94 ± 0.12 a	2.77 ± 0.12 a	0.74 ± 0.57 b	−4.18 ± 0.09 b	6.82 ± 0.68 a	1.52 ± 0.16 a
	SE	IMS	0.04 ± 0.00 b	0.10 ± 0.00 b	0.62 ± 0.11 bc	0.65 ± 0.11 b	0.05 ± 0.07 b	0.00 ± 0.00 b
		CMS	0.06 ± 0.00 a	0.11 ± 0.00 a	3.72 ± 0.10 a	4.67 ± 0.20 a	3.18 ± 0.42 a	0.20 ± 0.02 a
	NE	IMS	−0.89 ± 0.06 b	0.00 ± 0.06 b	7.17 ± 0.93 a	3.19 ± 0.93 a	0.57 ± 0.05 b	0.12 ± 0.00 b
		CMS	2.00 ± 0.12 a	2.88 ± 0.12 a	4.47 ± 0.59 b	0.49 ± 0.26 b	10.00 ± 1.10a	1.72 ± 0.18 a
2022	CE	IMS	−2.52 ± 0.15 b	−1.71 ± 0.15 b	16.11 ± 0.29 a	12.25 ± 0.23 a	−0.62 ± 0.11 b	−0.15 ± 0.02 b
		CMS	−0.14 ± 0.10 a	0.68 ± 0.10 a	3.23 ± 0.31 b	0.02 ± 0.38 b	2.95 ± 0.42 a	0.72 ± 0.12 a
	SE	IMS	0.08 ± 0.00 b	0.14 ± 0.00 b	0.07 ± 0.01 b	−0.05 ± 0.07 a	−0.06 ± 0.05 b	0.00 ± 0.00 a
		CMS	0.10 ± 0.00 a	0.17 ± 0.00 a	0.75 ± 0.24 a	−0.02 ± 0.39 a	0.95 ± 0.04 a	−0.03 ± 0.04 b
	NE	IMS	−2.44 ± 0.15 b	−1.57 ± 0.15 b	16.18 ± 0.29 a	12.2 ± 0.29 a	−0.68 ± 0.16 b	−0.15 ± 0.02 b
		CMS	−0.04 ± 0.10 a	0.85 ± 0.10 a	3.99 ± 0.33 b	0.00 ± 0.33 b	3.91 ± 0.46 a	0.69 ± 0.08 a

Note: CE, complementary effect, SE, selection effect, NE, net effect. IMS, maize-soybean relay intercropping, CMS, conventional maize-soybean intercropping. DE_{CO2}, direct CO_2 equivalent emissions, TE_{CO2}, total CO_2 equivalent emissions, EB, economic benefit of intercropping, NEB, net economic benefit of intercropping, $GHGI_Y$, yield scaled greenhouse gas emissions intensity, $GHGI_B$, economic benefit scaled greenhouse gas emissions intensity. Values are mean ± standard error. Different lowercase letters signify significant differences among intercropping in each term under the same crop growing season.

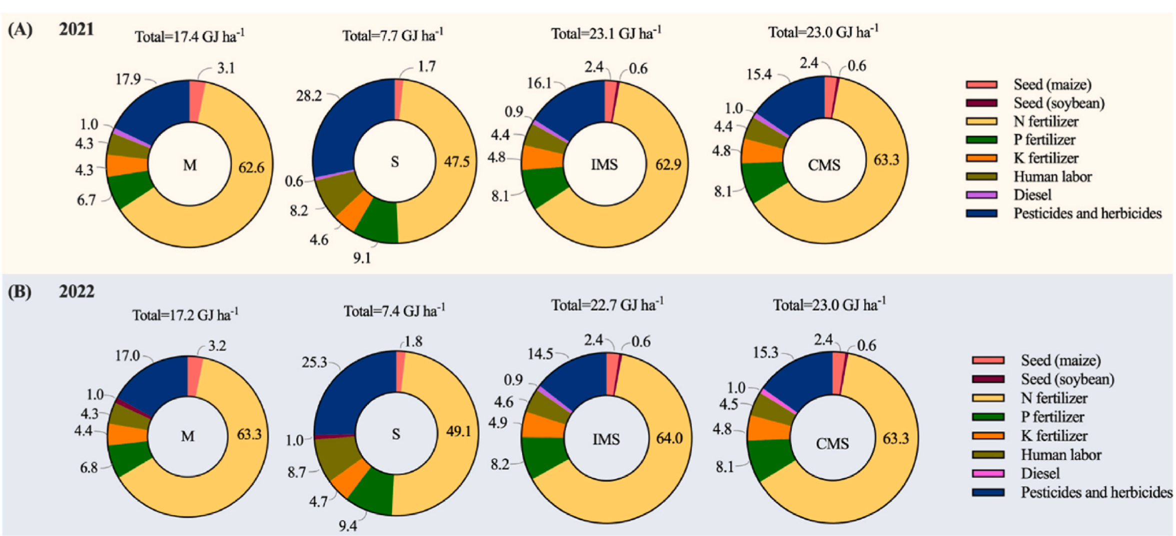

Fig. 5. Effects of cropping systems on energy budget. For an explanation of abbreviations M, S, IMS and CMS, please refer to Fig. 1.

22.3 % lower than those of CMS, respectively (Table 2). The CF of IMS was 1.2 % higher than that of M. However, the system yield, economic benefit, and energy output were significantly higher in IMS than in S. As a result, CF_Y, CF_B, CF_{NEB}, and CF_{EO} were reduced by 3.3 %, 25.5 %, 30.3 %, and 21.8 % in IMS compared to M, respectively. Moreover, the CF_Y, CF_B, CF_{NEB}, and CF_{EO} of IMS were 12.3 %, 25.5 %, 37.3 %, and 5.9 % lower than those of CMS, respectively. Similarity, the CF_Y, CF_B, CF_{NEB}, and CF_{EO} of IMS were 62.9 %, 28.5 %, 33.1 %, and 17.3 % lower than those of S, respectively (Table 2). Therefore, considering CF_Y, CF_B, and CF_{NEB} could provide a more comprehensive assessment of the environmental benefits of maize-soybean intercropping systems.

Moreover, IMS obtained a negative net effect of carbon footprint

Table 4
Effects of biodiversity on energy use in intercropping systems.

Year	Term	CS	NEO (GJ ha^{-1})	EUE	EP (kg MJ^{-1})	SEI (MJ kg^{-1})	PE
2021	CE	IMS	109.27 ± 13.07 a	13.38 ± 1.46 a	0.21 ± 0.00 a	4.78 ± 0.08 b	12.42 ± 1.55 a
		CMS	99.64 ± 2.95 a	12.60 ± 0.55 a	0.05 ± 0.01 b	15.36 ± 1.76 a	11.65 ± 0.32 a
	SE	IMS	1.95 ± 0.86 a	−0.89 ± 0.35 a	0.01 ± 0.01 b	0.11 ± 0.15 b	−0.92 ± 0.18 a
		CMS	2.57 ± 0.51 a	−1.22 ± 0.29 a	0.10 ± 0.01 a	4.17 ± 0.59 a	−1.27 ± 0.09 b
	NE	IMS	111.22 ± 13.78 a	12.5 ± 1.38 a	0.21 ± 0.02 a	4.89 ± 0.13 b	11.5 ± 1.50 a
		CMS	102.21 ± 3.32 a	11.38 ± 0.39 a	0.15 ± 0.02 b	19.53 ± 2.34 a	10.38 ± 0.41 a
2022	CE	IMS	97.07 ± 18.43 a	12.87 ± 2.50 a	0.46 ± 0.02 a	2.18 ± 0.19 b	11.9 ± 0.58 a
		CMS	67.07 ± 14.97 a	9.87 ± 0.79 a	0.11 ± 0.02 b	7.78 ± 0.51 a	8.78 ± 0.61 b
	SE	IMS	−8.21 ± 6.25 a	−1.16 ± 0.63 a	−0.01 ± 0.01 b	−0.02 ± 0.02 b	−1.19 ± 0.76 b
		CMS	−4.97 ± 2.70 a	0.10 ± 0.21 a	0.02 ± 0.01 a	0.50 ± 0.08 a	0.19 ± 0.31 a
	NE	IMS	88.86 ± 13.38 a	11.71 ± 1.88 a	0.46 ± 0.02 a	2.16 ± 0.22 b	10.71 ± 0.40 a
		CMS	62.1 ± 12.83 a	9.97 ± 0.68 a	0.13 ± 0.03 b	8.28 ± 0.46 a	8.97 ± 0.32 b

Note: CE, complementary effect, SE, selection effect, NE, net effect. IMS, maize-soybean relay intercropping, CMS, conventional maize-soybean intercropping. NEO, net energy output, EUE, energy use efficiency, EP, energy productivity, SEI, specific energy, PE, energy profitability. Values are mean ± standard error. Different lowercase letters signify significant differences among intercropping in each term under the same crop growing season.

(mean value: 0.8 ± 0.4 kg CO_2-eq ha^{-1}); in contrast, the net effect of carbon footprint was 1.9 kg CO_2-eq ha^{-1} in CMS (Table 5). The net effect of CF_Y, CF_{EB}, and CF_{NEB} was 32.4, 23.5, and 33.8 times lower in IMS than in CMS due to the complementary effect rather than the selection effect. Besides, the net effect of CF_{EO} was 7.8 times lower in IMS than in CMS due to a 6.7 times lower complementary effect. The complementary effect of relay strip intercropping benefits direct and indirect CO_2 emissions (Fig. S7 and S8). In short, IMS had more advantages in reducing carbon footprints in current agricultural production activities.

4. Discussion

4.1. *Relay strip intercropping has achieved higher yields and lower direct CO_2-equivalent emissions, thereby realizing a lower carbon footprint*

On average, the maize-soybean relay strip intercropping (IMS) obtained a grain yield of 9.1 t ha^{-1} and a land equivalent ratio (LER) of 1.8 (Fig. 1A and 3A). The yield advantage of IMS was more robust than conventional maize-soybean intercropping (CMS), resulting from win-wins in IMS and trade-offs in CMS. Intercropping enhances land productivity through complementary utilization of resources (Zhang et al., 2021b). On the one hand, appropriate competitive and complementary utilization of water and nutrients between the component crops in intercropping promotes crop growth, and enhances carbon fixation in the leaf (Chen et al., 2019; Fu et al., 2023; Yin, et al. 2016, 2018). Then, the improved leaf functional traits benefit photosynthetic assimilates partition from source to sink and yield gain. On the other hand, intercropping improves crop growth to strengthen nutrient absorption and reduces nitrogen loss to the environment, thereby reducing environmental costs (Wang et al., 2023b; Zhang et al., 2024b). Intercropping enhances yield not only through the efficient use of nitrogen fertilizers but also through the improved utilization of phosphorus fertilizers, has been shown to significantly boost phosphorus-related efficiencies. The phosphorus uptake efficiency, recovery efficiency, partial factor productivity of phosphorus fertilizer, and crop phosphorus efficiency of maize-soybean intercropping increased by 60 %, 58 %, 24 %, and 10.5 % compared with monoculture maize, respectively (Ahmad et al., 2025). Moreover, intercropping can also increase crop yield by maintaining biodiversity, increasing the abundance of beneficial microorganisms, and improving the efficiency of nitrogen fertilizer use (Fu et al., 2019; Li et al., 2025). Compared with monoculture, intercropping increased maize yield by 31.17 % and soil nitrogen by 14.53 %, and improved relative abundance of *Sphingomonas* and *Gemmatimonas* (Zhang et al., 2024a).

Indeed, the complementary effect (CE) rather than the selection effect (SE) led to a higher net effect (NE) in IMS (Fig. 2). Unfortunately, the more robust resources competitive use for maize suppressed soybeans in the CMS (Fig. 3C). This is consistent with the previous studies showing that a reasonable resource competitive use benefit for overyielding and enhancing resource use in maize-wheat intercropping, but a robust resource competitive use led to yield disadvantage and resource wasting in faba bean-wheat intercropping (Fan et al., 2006; Zhang and Li, 2003). Therefore, to obtain higher yield advantages with more efficient use of resources in intercropping, suitable species combinations and reasonable crop configurations are essential. Competition can be alleviated by increasing resource supply or interspecific distance (Chen et al., 2017;

Table 5
Effects of biodiversity on carbon footprint in intercropping systems.

Year	Term	CS	CF	CF_Y	CF_{EB}	CF_{NEB}	CF_{EO}
			(Mg CO_2-eq ha^{-1})	(kg CO_2-eq ha^{-1})	(kg CO_2-eq CNY^{-1})	(kg CO_2-eq CNY^{-1})	(kg CO_2-eq KJ^{-1})
2021	CE	IMS	−0.09 ± 0.06 b	0.95 ± 0.03 b	0.21 ± 0.01 b	0.52 ± 0.10 a	8.53 ± 2.95 b
		CMS	2.77 ± 0.12 a	8.1 ± 0.82 a	1.83 ± 0.19 a	−2.05 ± 0.29 b	32.07 ± 1.45 a
	SE	IMS	0.09 ± 0.00 b	0.03 ± 0.09 b	0.00 ± 0.01 b	0.02 ± 0.00 a	−0.43 ± 0.07 a
		CMS	0.11 ± 0.00 a	3.56 ± 0.48 a	0.20 ± 0.02 a	−0.51 ± 0.01 b	−1.17 ± 0.07 b
	NE	IMS	0.00 ± 0.06 b	0.98 ± 0.06 b	0.22 ± 0.00 b	0.54 ± 0.1.0 a	8.1 ± 2.9 b
		CMS	2.88 ± 0.12 a	11.66 ± 1.3 a	2.02 ± 0.21 a	−2.56 ± 0.29 b	30.9 ± 1.41 a
2022	CE	IMS	−1.70 ± 0.15 b	−0.41 ± 0.11 b	−0.10 ± 0.02 b	−0.27 ± 0.08 b	−0.39 ± 3.19 b
		CMS	0.68 ± 0.10 a	3.61 ± 0.46 a	0.88 ± 0.14 a	13.2 ± 3.92 a	30.99 ± 2.22 a
	SE	IMS	0.14 ± 0.00 b	−0.09 ± 0.06 b	0.00 ± 0.00 a	0.00 ± 0.00 a	−0.59 ± 0.98 a
		CMS	0.17 ± 0.00 a	1.01 ± 0.05 a	−0.05 ± 0.05 a	−1.21 ± 0.12 b	0.75 ± 0.44 a
	NE	IMS	−1.56 ± 0.15 b	−0.50 ± 0.17 b	−0.1 ± 0.03 b	−0.27 ± 0.07 b	−0.98 ± 4.17 b
		CMS	0.85 ± 0.10 a	4.62 ± 0.50 a	0.83 ± 0.09 a	11.99 ± 3.94 a	31.74 ± 2.64 a

Note: CE, complementary effect, SE, selection effect, NE, net effect. IMS, maize-soybean relay intercropping, CMS, conventional maize-soybean intercropping. CF, carbon footprint, CF_Y, grain yield scaled carbon footprint, CF_{EB}, economic benefit scaled carbon footprint, CF_{NEB}, net economic benefit scaled carbon footprint, CF_{EO}, energy output scaled carbon footprint. Values are mean ± standard error. Different lowercase letters signify significant differences among cropping systems in each crop growing season.

Fan, et al. 2018, 2019; Hu et al., 2016; Yang et al., 2015). Finally, the greater interspecific distance and higher complementary use of resources led to more robust yield advantages in IMS than in CMS (Fig. 6). In CMS, the yield advantage was contributed by SE rather than CE, indicating competitive use of resources. When the yield advantage contributed by SE, it means competitive utilization of resources, which will lead to instability of the system and potentially lead to production reduction in the long term (Wang et al., 2021).

In this study, the cumulative emissions of N_2O were lower in IMS than in monocropping maize (M) and CMS (Fig. S4). This resulted in notably declined in global warming potential (GWP) of IMS by 28.2 % and 27.6 % when compared to M and CMS, respectively (Fig. 4). This decline is likely due to the competitive use of nitrogen in intercropping, promotes the conversion of soil NH_4^+ to NO_3^- and reduces nitrogen release, thereby resulting in lower reactive nitrogen emissions than in monoculture (Chen, et al. 2017, 2019; Hu et al., 2016). Meanwhile, intercropping improves soil carbon and changes the soil C:N ratio to enhance soil nitrogen immobilization rate and reduce nitrogen release into the environment (Cong et al., 2015; Regehr et al., 2015). Besides, in maize-soybean intercropping, soybeans can fix nitrogen and transfer it to maize to meet the maize nitrogen demand to a certain extent, which results in declining chemical nitrogen fertilizer use and greenhouse gas emissions (Chu et al., 2004). Moreover, the competitive use of water between the component species led to a water deficit and promoted N_2O emissions (Chen, et al. 2019b; Rahman et al., 2016; Zhang et al., 2020b). Intercropping recruited specialized rhizosphere bacterial communities with different strategies, increasing the diversity of maize soil bacterial communities and reducing network complexity, thereby altering the greenhouse gas emission potential in the soil-root-plant system (Fu et al., 2019; Li et al., 2025).

4.2. *Relay strip intercropping achieved lower carbon footprint via the complementary effect*

The cumulative CO_2 and CH_4 emissions were highest in CMS (11,073.3 kg ha^{-1}) and lowest in IMS due to higher emissions of soybean (Fig. S5 and S6). The soil CO_2 emissions flux showed an increase after applying nitrogen fertilizer, but it has multiple small emission peaks, indicating that CO_2 emission not only depends on the impact of fertilizer inputs, but may also be affected by plant growth and weather conditions. The previous studies documented that intercropping improves soil carbon pools and reduces soil carbon emissions (Cong et al., 2015; de Araujo Santos et al., 2019; Li et al., 2023). Meanwhile, CO_2 and CH_4 emissions are positively associated with precipitation (Guo et al., 2023; Wei et al., 2010). However, soybean growth in CMS was suppressed by the competitive use of light and water of maize (Fan, et al. 2018, 2019; Rahman et al., 2016). In other words, good legume growth improves soil carbon pools and benefits the alleviating of carbon emissions in IMS compared with CMS. Consistent results were observed that the complementary effect of relay strip intercropping benefits for direct and indirect CO_2 emissions (Fig. S7 and S8). Additionally, the yield, economic benefit, and LER-scaled greenhouse emissions intensity (GHGI) of IMS were the lowest due to robust crop productivity and cleaner production in IMS than the other (Fig. 4).

In this study, we confirmed that the complementary effect of intercropping benefits to enhance economic return and alleviate environmental costs (Tables 3 and 5). Researchers commonly focus on biodiversity's impact on crop productivity and nutrient use, and reported that nitrogen and phosphorus use in cerea-legumes intercropping systems mainly contributed by CE rather than SE (Li et al., 2018; Zhang, et al. 2021a). Direct and indirect equivalent CO_2 emissions determine the CF and are also closely related to crop productivity (Yadav et al., 2018). In the current study, the CF was lower in IMS than in monocropping maize and CMS due to low direct equivalent CO_2 emissions and higher yield gain. Consequently, the yield scald carbon footprint (CF_Y) of IMS was 3.3 % and 12.3 %, notably lower than those of M and CMS (Table 2). The results are consistent with the previous study that the intercropping increased crop yields by 15.6 %–49.9 % and reduced environmental footprints by 17.3 % in semi-arid areas (Chai et al., 2021). On the one hand, intercropping can alleviate direct greenhouse gas emissions through interspecific interactions (Wang et al., 2023b; Zhang et al., 2024b). On the other hand, intercropping improves soil carbon storage capacity and crop yields (Roohi et al., 2022). Similar results were observed in that the yield, economic benefit, and energy output scaled carbon footprint of IMS were lower than those of M and CMS. This suggests that the IMS provides a way to achieve a win-win scenario for agricultural cleaner production (Fig. 6).

4.3. *The complementary use of energy indicated the sustainable development of the relay strip intercropping system*

The total energy input increased by 32.3 % and 192.7 % in IMS compared with monocropping maize and soybean, but the net energy output of IMS was 31.4 % and 77.0 % higher than that of M and S

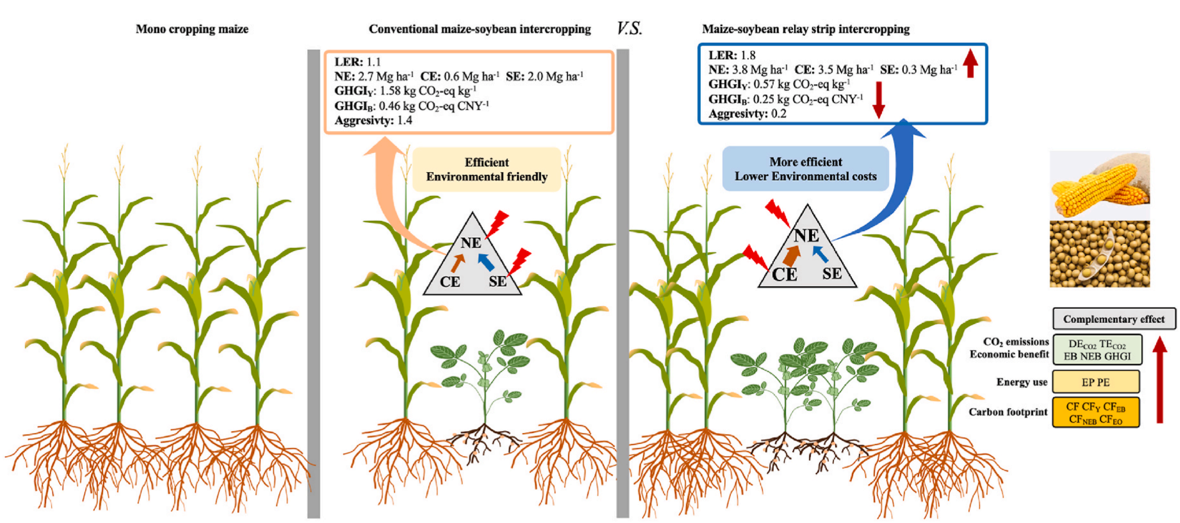

Fig. 6. Model diagram of biodiversity effects on crop productivity and environmental impacts in intercropping. LER, land equivalent ratio, NE, net effect, CE, complementary effect, SE, selection effect, $GHGI_Y$ and $GHGI_B$, grain yield and economic benefit scaled greenhouse gas emissions intensity. DE_{CO2}, direct CO_2 equivalent emissions, TE_{CO2}, total CO_2 equivalent emissions, EP, energy productivity, PE, energy profitability, CF, carbon footprint, CF_Y, grain yield scaled carbon footprint, CF_{EB}, economic benefit scaled carbon footprint, CF_{NEB}, net economic benefit scaled carbon footprint, CF_{EO}, energy output scaled carbon footprint.

(Table 1). This is inconsistent with the study conducted in semi-arid areas where the total energy input was lower in maize-wheat replacement intercropping (Yin et al., 2022). Because we conducted a full additive maize-soybean intercropping in a rainfed area, and the resource inputs were more than the corresponding monoculture. Besides, the energy use efficiency and profitability were similar with M, suggesting IMS had yield and energy use advantages (Figs. 5 and 6).

The energy output of IMS was higher than that of CMS, which may be due to planting density. Both IMS and CMS were additive intercropping, and the density was twice that of replacement intercropping. The weak light radiation for soybeans in CMS hinders their growth, resulting in lower energy output than that of IMS. Previous studies have also investigated the effects of different planting densities on crop light radiation and output. A medium density (8 maize plants m^{-2}) of intercropped maize was found to be the most efficient in utilizing radiation and water. Moreover, the economic benefit of medium-density maize was $1300 per hectare, which is 1.6 times that of monoculture maize and 1.8 times that of monoculture soybeans (Raza et al., 2022). Additionally, The biodiversity and litter of CMS was lower than that of IMS. In intercropping systems, the diverse straw types significantly influence straw mass loss in both the same plot and home plots, with maize-peanut straw mixtures showing a higher home-field advantage than maize-soybean straw mixtures (Surigaoge et al., 2023).

Previous studies have shown that the production inputs of soybeans and peanuts are associated with greenhouse gas emissions, and the main contributors are chemical fertilizers and diesel fuel (Nia et al., 2024). This aligns with the findings of our study, which highlights the significant impact of nitrogen fertilizer on energy input, accounting for 47.5–63.3 % (Fig. 5). However, it's important to note that chemical nitrogen fertilizer has led to a 35 % increase in greenhouse gas emissions from agricultural production, posing a significant threat to the ecological environment (Benbi, 2018; Fan et al., 2005). However, intercropping reduces the application of pesticides, thereby alleviating environmental pollution. Compared with monoculture, intercropping significantly reduces the incidence of soybean root rot and changes the diversity and pathogenicity of *Fusarium* species (Chang et al., 2020). Moreover, light intensity affects the expression of defense-related genes in soybeans, thereby influencing their resistance to *Soybean mosaic virus*. Soybeans balance resource allocation between growth and defense by regulating gene expression under different light intensities, providing a theoretical basis for *Soybean mosaic virus* resistance in intercropped soybeans(Shang J et al., 2023). Compared with CMS, the complementary effect accounts for energy productivity, specific energy, and energy profitability in IMS (Table 4). This suggests that more efficient complementarity energy use supports the sustainable development of IMS (Fig. 6). Therefore, the practice of intercropping facilitates the efficient utilization of resources and enhances land productivity. Particularly in developing countries, where resource scarcity is a significant challenge, adopting intercropping can reduce the reliance on resource inputs such as pesticides, fertilizers, and irrigation, without compromising land productivity.

This study primarily focuses on greenhouse gas emissions, yield, carbon footprint, and economic benefits in strip intercropping systems. However, it did not conduct an in-depth analysis of the mechanisms by which rhizosphere microorganisms drive greenhouse gas emissions. Therefore, future research should further focus on the microbial characteristics of the root-rhizosphere to provide a theoretical basis for a more comprehensive investigation into the differences in greenhouse gas emissions and their underlying mechanisms.

5. Conclusions

The maize-soybean relay strip intercropping provides approaches to achieve agricultural cleaner production by enhancing energy productivity and obtains yield advantages with a low carbon footprint. The maize-soybean relay strip intercropping obtained a land equivalent ratio and net effect of 1.8 and 3.8 Mg ha^{-1}. Although the total energy input of the maize-soybean relay strip intercropping system increased, its net energy and output economic benefits were significantly higher than those of monoculture maize and soybeans. The lower carbon footprint resulted from fewer direct equivalent CO_2 emissions in the maize-soybean relay strip intercropping than monocropping maize and conventional maize-soybean intercropping. Besides, the complementary effect rather than the selection effect accounts for yield advantages, efficient energy use, and cleaner production in maize soybean relay strip intercropping systems. These research findings indicate that relay strip intercropping has the sustainable potential to enhance productivity and reduce environmental impacts in rain-fed regions. It provides a valuable reference for practitioners and policymakers in agricultural production across both developed and developing countries and regions, with the aim of achieving cleaner and more sustainable agricultural development.

CRediT authorship contribution statement

Zhidan Fu: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ping Chen:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Ping Lin:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis. **Yiling Li:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Kai Luo:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis. **Chao Gao:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Tian Pu:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis. **Yuze Li:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis. **Yushan Wu:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis. **Xiaochun Wang:** Writing – review & editing, Writing – original draft, Resources, Methodology, Formal analysis. **Taiwen Yong:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Wenyu Yang:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that the research was carried out in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.126707.

Data availability

Data will be made available on request.

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