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Chicken manure-based organomineral fertilization improves nutrient use efficiency and reduces greenhouse gases (GHGs) emissions in maize

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ABSTRACT

Organomineral fertilizers (OMF) represent an opportunity to develop locally sourced fertilizers to decarbonize grain value chains. A two-location field study comparing OMF and mineral fertilizers (MF) agronomic and environmental performance was established at two Peruvian valleys, the environmental impacts of maize grain produced with locally produced OMF and imported MF were modelled through cradle-to-gate life cycle analysis (LCA). The carbon footprints (CF) of OMF resulted smaller than those of imported MF. Fully replacing MF with OMF results in equivalent grain yield, 43% higher phosphorus agronomic efficiency and reduced cradle-to-gate greenhouse gas (GHG) emissions in up to 232 kg carbon dioxide (CO_2) eq Mg^{-1} grain. Estimated NOx emissions, nutrient lixiviation and mineral resource depletion were reduced as well, providing support for OMF as a tool for sustainable grain production.

1. Introduction

In Peru, maize is produced by over 170,000 growers, accounts for 1.9% of the gross production value of agriculture (MIDAGRI, 2024), and represents the primary protein source for livestock in Peru (MIDAGRI, 2023). Nitrogen (N), phosphorus (P), and potassium (K) mineral fertilizers (MF) are employed at an increasing rate to produce maize. Globally, maize production relies on high and often increasing applications of N, P, and K mineral fertilizers, particularly in intensive production systems (Ciampitti and Vyn, 2014; Luo et al., 2024; Otto et al., 2022; L. Zhang et al., 2023). While MF improves yield and land use efficiency (Jones-Garcia and Krishna, 2021), their manufacture and use are energy-intensive and associated with GHG emissions, nutrient losses as ammonia and lixiviates, and pressure on non-renewable resources (Bijay and Craswell, 2021; M. Chen and Graedel, 2015; Cordell et al., 2009; Jwaideh et al., 2022; Liu et al., 2021; Sutton et al., 2013; Tesfaye et al., 2021; Ushakova et al., 2023; F. Zhang et al., 2017). Approximately one-third of the global agriculture CF is attributed to fertilizer manufacture and application, and maize is among the highest-emitting crops (Morales-Castilla et al., 2020; Yan et al., 2015). This footprint is mainly driven by MF, with nitrogen fertilizers accounting for 65% of the fertilizer-related emissions (Vargas et al., 2023), primarily through N_2O emissions (Grace et al., 2011; Tian et al., 2020), although reported emission magnitudes vary across regions and management practices.

Organic matter (OM) enhances nutrient use efficiency (NUE) and soil health (Erenstein et al., 2022; Gezahegn, 2021; Jones-Garcia and Krishna, 2021), and its combined application with MF has been shown to improve crop growth and yield, particularly in nutrient-depleted soils (Y. Chen et al., 2018). In maize systems, OM contributes to more sustained nutrient availability through gradual mineralization and interactions with mineral nutrients, supporting improved nutrient uptake (He et al., 2022; Jjagwe et al., 2020; Jones et al., 2005; Nadeem Shah

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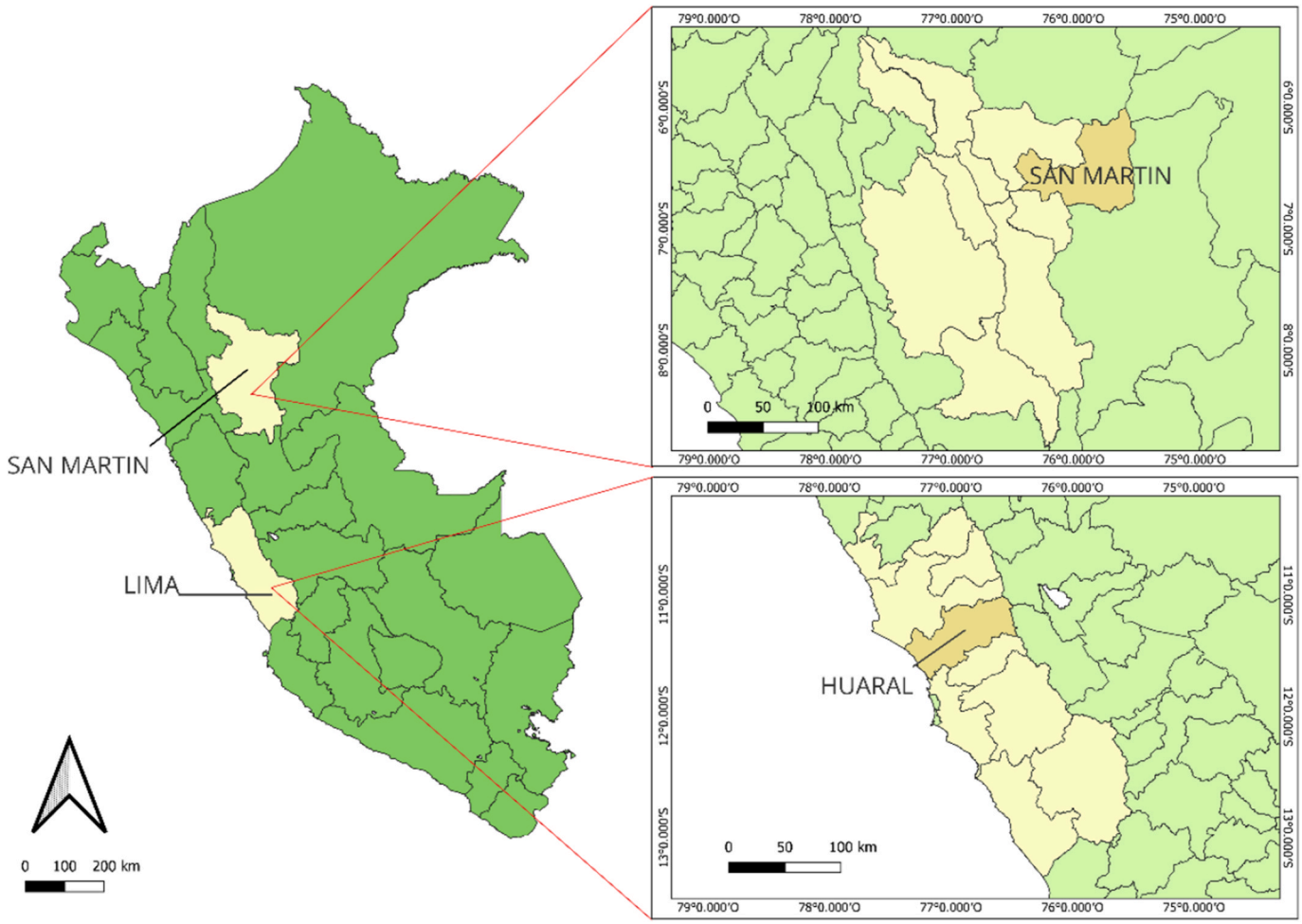

Fig. 1. Field trial locations.

Table 1
Nutrition plans.

Trial location	Treatment	Nutrient applied (kg ha^{-1})	Product applied (kg ha^{-1})
Huaral	Control	0 (N); 0 (P); 0 (K)	Untreated
	OM	86 (N); 48 (P); 65 (K)	3120 (SuperSuelo™)
	OMF	367.06 (N); 73.86 (P); 200.29 (K)	2115 (BioC Nitro™); 349 (BioC Phos™); 655 (BioC Potasio™)
	MF	367.06 (N); 73.86 (P); 200.29 (K)	655 (Urea); 368 (DAP); 484 (K_2SO_4)
Juan Guerra	Control	0 (N); 0 (P); 0 (K)	Untreated
	OM	74 (N); 41 (P); 56 (K)	2697 (SuperSuelo™)
	OMF	324.57 (N); 62.93 (P); 162.07 (K)	1883 (BioC Nitro™); 292 (BioC Phos™); 522 (BioC Potasio™)
	MF	324.57 (N); 62.93 (P); 162.07 (K)	584 (Urea); 314 (DAP); 326 (KCl)

et al., 2023; Priya et al., 2024; Shaji et al., 2021; Zhu et al., 2023).

Organo-mineral fertilizers (OMF) combine MF with OM (Antille et al., 2013; Kominko et al., 2019) delivering nutrients more gradually than MF alone, thereby improving nutrient availability and soil biological activity. OMF have been reported to achieve yields comparable to or greater than MF, promoting beneficial soil microbial activity (Ayeni et al., 2012; Saha et al., 2019; Uddin et al., 2023; Yıldız and Dizikısa, 2023) and improving NUE in up to 20% (Dania et al., 2022). OMF production supports circular economy strategies by valorizing organic waste and reducing the dependence on imported MF (Bouhia et al., 2022; Kominko et al., 2021).

Evidence remains limited for direct comparisons of locally produced OMF and imported MF across contrasting Latin American agroecosystems, particularly using combined NUE and cradle-to-gate LCA. This study addresses this gap by integrating LCA and NUE analysis to evaluate agronomic performance and environmental impacts of using an OMF produced from layer manure in maize systems across two distinct agroecosystems in Peru, including environmental impact mitigation on GHG and other C and N emissions, N and P lixiviates and pressure on non-renewable P and K resources.

2. Materials and methods

2.1. Site description and soil analysis

Two field trials were conducted at the National Institute for Agrarian Innovation (INIA) Juan Guerra and Huaral Agricultural Experimental Stations: The former a low elevation tropical dry forest in the Amazon basin (227 masl) and the latter a subtropical desert coastal landscape (130 masl) (Fig. 1). Juan Guerra presents a slightly inclined physiography (0–4%), 28.1 °C annual average temperature and 1160 mm year^{-1} precipitation, with a marked dry season from June to October. In contrast, Huaral presents similar physiography, lower mean annual temperature (20.3 °C), and very low precipitation (23.6 mm year^{-1} precipitation), with a shorter dry period from May to August. Baseline soil characterization was performed prior to sowing on the 0–30 cm layer from twenty composite samples per experimental unit at each site (Bazán, 2017) (SM 1). Soil at Juan Guerra was clayey, near-neutral in

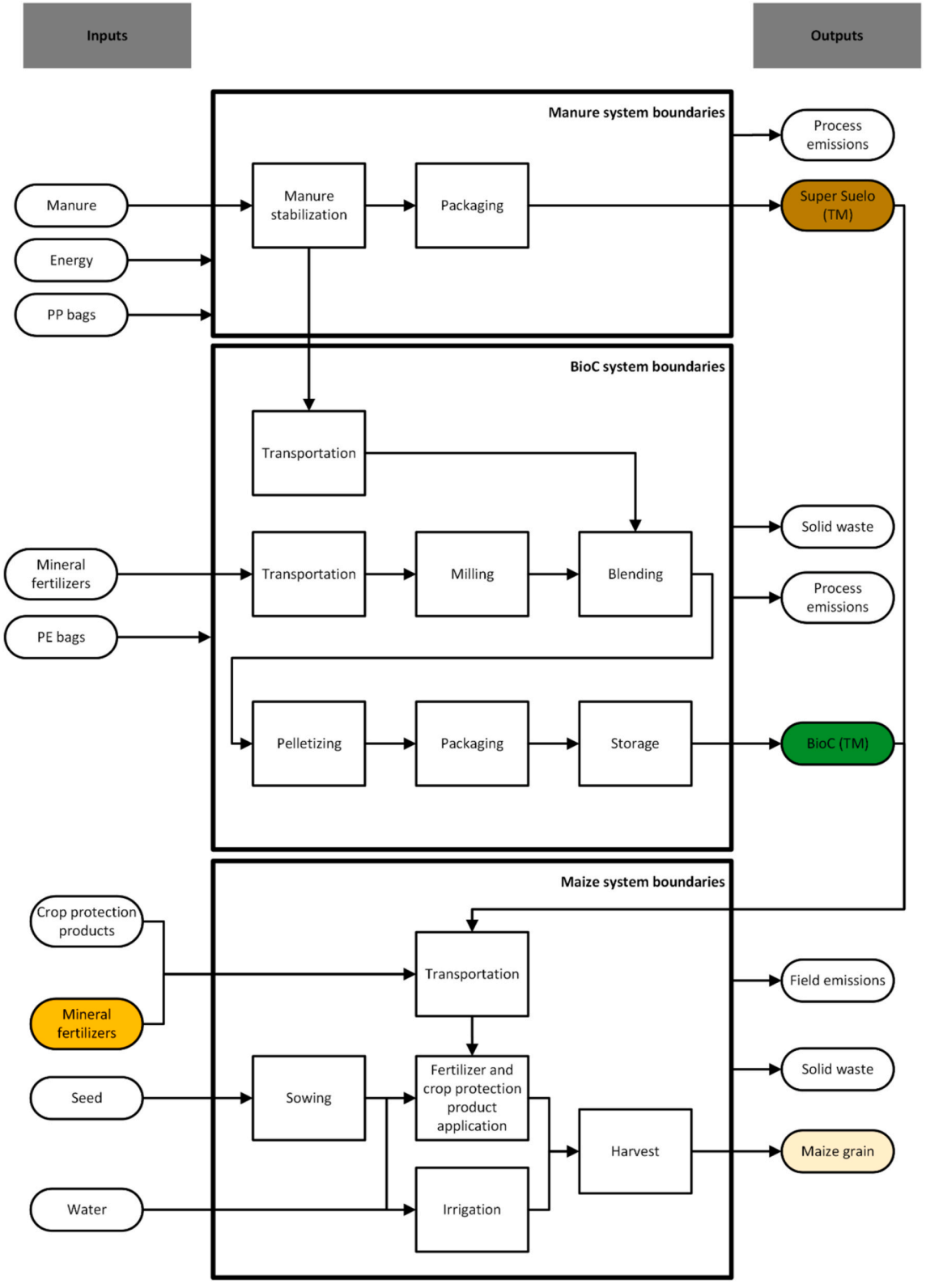

Fig. 2. LCAs system boundaries.

pH, with low salinity, and moderate soil organic carbon (SOC) and nutrient availability. Huaral soil was sandy clay loam, moderately alkaline, characterized by high calcium carbonate content, low phosphorus availability, and moderate SOC levels.

2.2. Trial design

Field trials were established using a completely randomized block design with five blocks. The Huaral field was divided into 6 × 4 m plots, each with five ridges 80 cm apart. INIA 619 Megahybrid maize seed was sown at 2–3 seeds per hole, with 20 cm between plants on April 25th,

Table 2
Initial and final SOC stocks and changes.

Location	Treatment	SOC* (%)		Bulk Density (gr cm^{-3})		SOC stock (Mg ha^{-1})		Δ SOC stock (Mg ha^{-1})
		Initial	Final	Initial	Final	Initial	Final	
Huaral	Control	0.89 ± 0.14	2.00 ± 0.18^{b}	1.48 ± 0.02	1.48 ± 0.02	39.34 ± 6.42	88.65 ± 8.69	49.31 ± 9.69
	OM	0.87 ± 0.19	2.08 ± 0.05^{b}	1.48 ± 0.03	1.48 ± 0.03	38.89 ± 8.31	92.78 ± 2.75	53.89 ± 9.74
	OMF	1.16 ± 0.48	2.22 ± 0.06^{a}	1.47 ± 0.02	1.47 ± 0.03	51.18 ± 21.02	97.52 ± 1.73	48.93 ± 10.85
	MF	1.10 ± 0.22	2.06 ± 0.09^{b}	1.47 ± 0.03	1.47 ± 0.02	48.59 ± 10.43	91.23 ± 2.98	40.05 ± 20.95
	Mean	1.01 ± 0.30	2.09 ± 0.13	1.48 ± 0.03	1.48 ± 0.03	44.50 ± 13.06	92.54 ± 5.56	48.04 ± 13.54
Juan Guerra	Control	0.99 ± 0.20	1.10 ± 0.14	1.33 ± 0.18	1.43 ± 0.09	39.24 ± 8.11	47.22 ± 6.38	7.98 ± 4.07
	OM	0.99 ± 0.19	1.09 ± 0.11	1.48 ± 0.17	1.45 ± 0.11	43.24 ± 7.28	47.87 ± 7.49	4.63 ± 6.57
	OMF	0.88 ± 0.15	1.11 ± 0.12	1.53 ± 0.23	1.35 ± 0.10	39.95 ± 7.69	44.71 ± 5.28	7.78 ± 9.53
	MF	0.92 ± 0.25	1.13 ± 0.15	1.34 ± 0.10	1.50 ± 0.19	39.94 ± 9.32	50.62 ± 9.59	10.67 ± 4.43
	Mean	0.94 ± 0.19	1.11 ± 0.12	1.42 ± 0.18	1.43 ± 0.13	39.84 ± 7.82	47.61 ± 7.09	7.76 ± 6.37

*Means with different letters were significantly different ($p < 0.05$, $n = 5$).

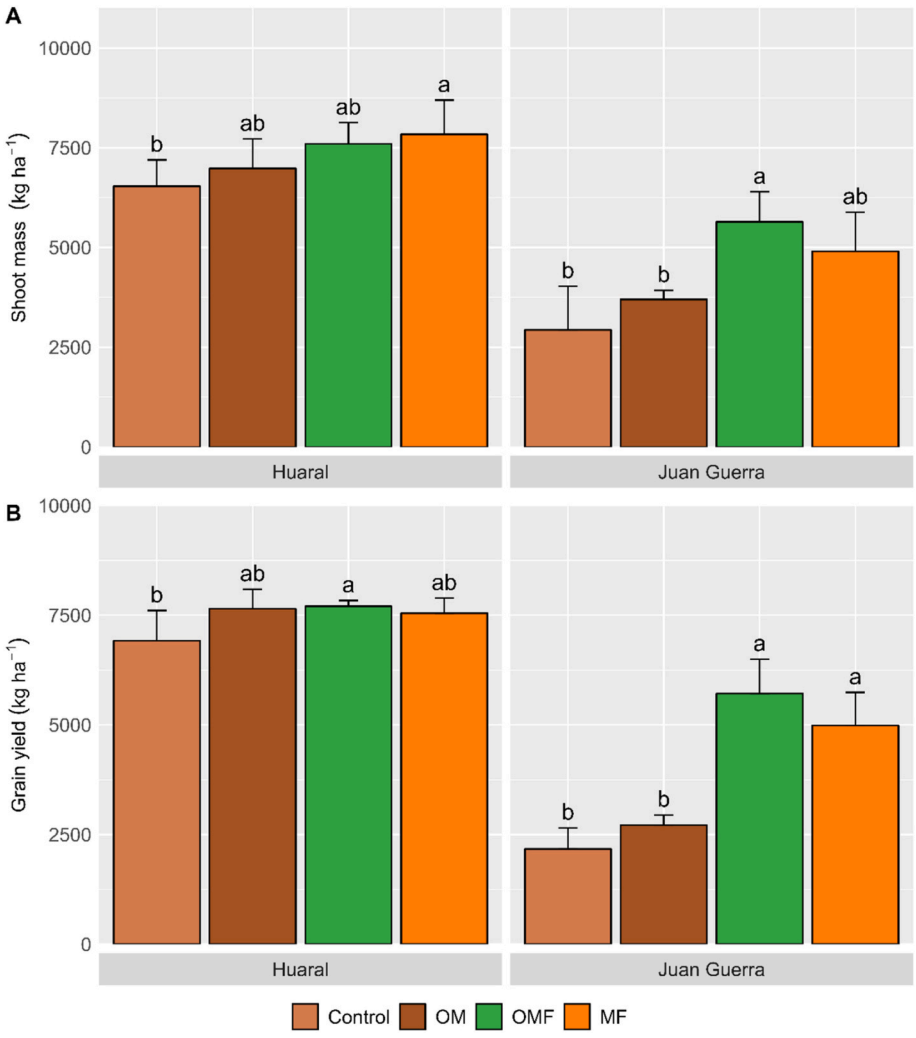

Fig. 3. Shoot biomass (A) and grain yield (B). Bars with different lowercase letters are significantly different ($p < 0.05$, $n = 5$).

2023. The Juan Guerra field was divided into 5 × 4 m plots, each with six ridges 80 cm apart. Marginal 28 Tropical maize seed was sown at 3–4 seeds per hole, with 35 cm between plants on May 12th, 2023.

Unfertilized control (Control), OM, OMF, and MF treatments were evaluated in both trials. OMF and MF fertilization doses were adjusted to the nutritional requirements to yield 10 Mg grain ha^{-1} (INIA, 2008, 2012). Nutrient contributions from the soil were further refined by considering an annual mineralization rate of 3% of the organic nitrogen bound to soil organic matter (Brady and Weil, 1999) along with phosphorus and potassium availability from the baseline soil characterization. OM was applied on a mass-equivalent basis to the OMF application rate at each field site (Table 1). SuperSuelo™ (160 g C kg^{-1} OC) (Vida al Suelo, Lima), a treated layer manure product was used as OM; BioC Nitro™, BioC Phos™ and BioC Potasio™ (60 g C kg^{-1} OC) (Vida al Suelo, Lima) were used as OMF; and generic urea, diammonium phosphate (DAP), potassium chloride (KCl) and potassium sulfate (K_2SO_4) were used as MF. BioC fertilizers consist of pellets produced by blending stabilized poultry manure with mineral nutrient sources and

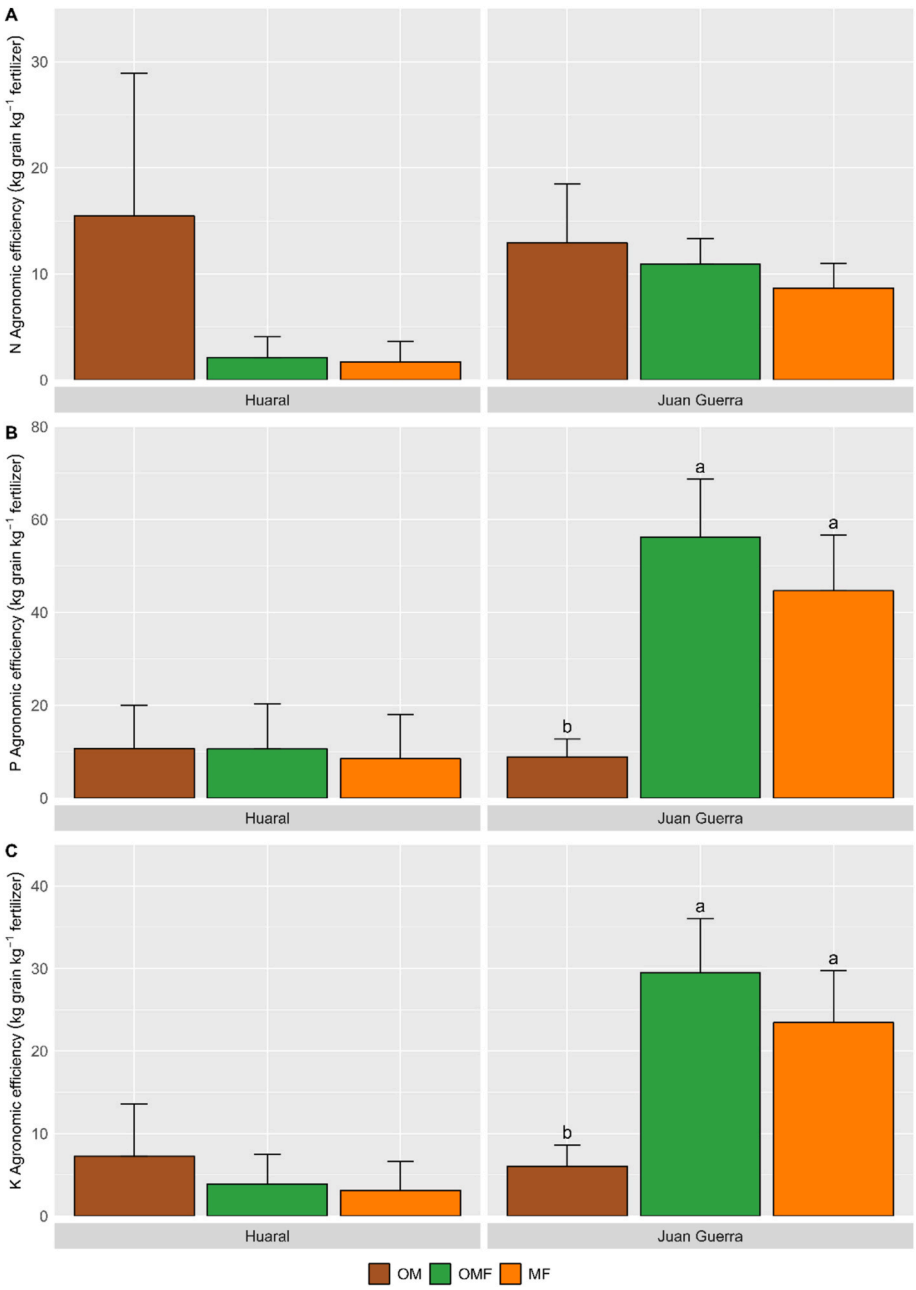

Fig. 4. Nitrogen, phosphorus and potassium agronomic efficiency. Bars with different lowercase letters are significantly different ($p < 0.05$, $n = 5$).

compacting the mixture into a physically homogeneous, agronomically manageable product. At Huaral, irrigation was applied at approximately 15-day intervals, resulting in a cumulative water input of ~6250 m^3 ha^{-1}. At Juan Guerra, irrigation was restricted to the dry season, using approximately 6000 m^3 ha^{-1}.

2.3. Soil organic carbon

Changes in SOC before sowing and after harvest were evaluated. Duplicate soil samples from each experimental unit were taken with a 5 cm diameter x 5 cm height aluminum cylinder. Bulk density (BD) of the first 30 cm layer of soil was estimated by the core method (Blake and Hartge, 1986). SOC was estimated by the Dumas method with an elemental analyzer (LECO CN828, LECO Ltd., Germany) (ISO/TC 190/SC 3, 1995), subtracting inorganic carbon from total carbon. The SOC stock for the 0–30 cm soil layer (Mg ha^{-1}) was estimated as:

$$\text{SOC stock} = \text{SOC} \times \text{BD} \times \text{d} \quad (1)$$

where SOC (%) and BD (g cm^{-3}) are defined as above, d is the sampling depth (30 cm) (Yigini and Panagos, 2016).

2.4. Shoot biomass and grain yield

Plants were harvested 146 and 111 days after sowing at Huaral and Juan Guerra. Shoot and grain samples were dried at 60 °C for 48 h and weighed as dry matter. Grain yield was calculated as:

$$\text{Grain yield}\left(\text{Mg ha}^{-1}\right) = \frac{(\text{FW} \times \text{DM} \times \text{G}) \times \text{CF}}{8600} \quad (2)$$

FW (kg ha^{-1}) is the cob fresh weight harvested per plot; DM (75%) is the grain dry matter from five cobs dried at 75 °C for 48 h; G (%) is the grain to cob weight ratio; CF converts plot yield to yield per hectare

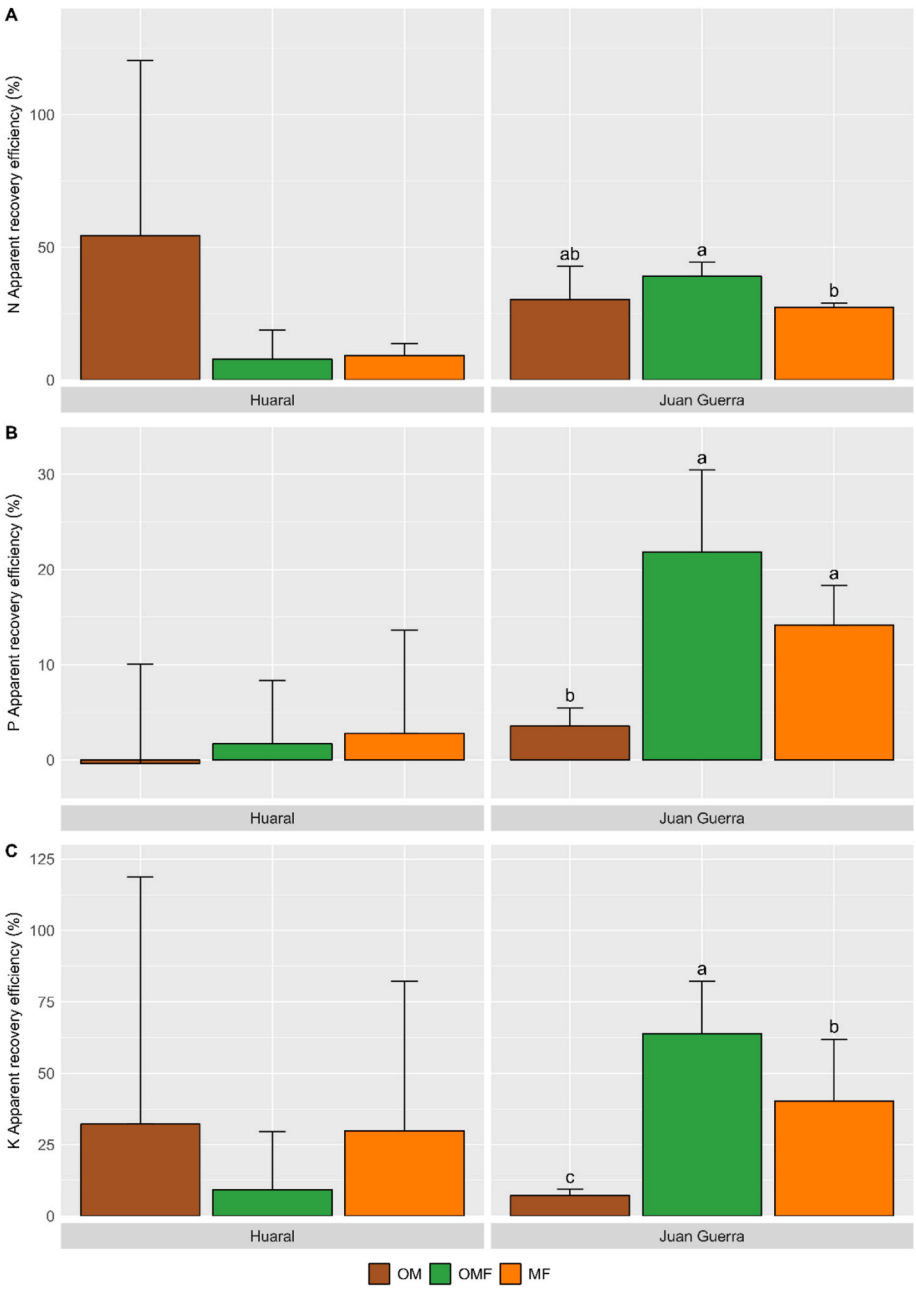

Fig. 5. Nitrogen, phosphorus and potassium apparent recovery efficiency. Bars with different lowercase letters are significantly different ($p < 0.05$, $n = 5$).

(10000 m^2 x plot size m^{-2}), and 8600 is a constant used to estimate commercial maize yield at the standard 14% moisture content (Espinosa-Calderón et al., 2013).

2.5. Shoot and grain nutrient content

N, P and K content was measured from shoot and grain samples. Shoot samples were rinsed in distilled water to remove debris and dried at 60 °C for 48 h. The samples were then ground with a mill and sieved through a 0.5 mm mesh. N content was estimated by micro-Kjeldahl digestion (Bremner, 1996) followed by colorimetric quantification (Technicon AAII, SEAL Analytical). P and K contents were estimated by HNO_3 digestion (Zasoski and Burau, 1977), followed by inductively coupled plasma optical emission spectroscopy quantification (ICP-OES, iCAP Series 7000, Thermo Scientific).

2.5.1. Agronomic efficiency and apparent recovery efficiency

Agronomic efficiency (AE) was calculated as the increment in grain yield per unit of nutrient applied (Fageria et al., 2008):

$$AE = \frac{(GY_f - GY_c)}{NS_a} \quad (3)$$

Where AE (kg grain yield kg^{-1} nutrient applied) is the agronomic efficiency, GY_f is the grain yield of a fertilized plot (kg ha^{-1}), GY_c is the grain yield of the unfertilized plot (kg ha^{-1}), and NS_a is the amount of nutrient applied through fertilization (kg ha^{-1}).

Apparent recovery efficiency (ARE) was calculated as the amount of nutrients absorbed by the crop per unit of nutrient applied (Fageria et al., 2008):

$$ARE = \frac{(NU_f - NU_c)}{NS_a} \times 100 \quad (4)$$

Table 3
Carbon footprint of organo-mineral fertilizers and mineral fertilizers.

Product	Product type	Origin	GWP (kg CO_2 eq per 50 kg bag)
Super Suelo	OM	Peru	0.7
Bio-C 16-03-02	OMF	Peru	41
Bio-C 11-29-03	OMF	Peru	36
Bio-C 02-02-37	OMF	Peru	11
Bio-C 01-02-31	OMF	Peru	5
Bio-C 11-05-11	OMF	Peru	39
Bio-C 11-12-04	OMF	Peru	27
Bio-C 07-07-19	OMF	Peru	20.5
Urea	MF	China	146.2
Diammonium phosphate	MF	Rest of the World	84.8
Potassium sulfate	MF	Europe	18.5
Ammonium nitrate	MF	Rest of the World	150
Potassium chloride	MF	Europe	10.7

Table 4
Fertilization plans associated emissions.

Location	Plan	Product	Amount (kg ha^{-1})	GWP (kg CO_2 eq ha^{-1})	Total (kg CO_2 eq ha^{-1})
Huaral	MF	Urea	655	1131.8	2816.4
		Diammonium phosphate	367.5	623.3	
		Potassium sulfate	484	1061.3	
	OMF	BioC Nitro 16-3-2	2115	1808.9	2201.9
		BioC Phos 11-29-3	349	251	
		BioC Potasio 2-2-37	655	142	
Juan Guerra	MF	Urea	584	1009.9	1623.1
		Diammonium phosphate	314	532.7	
		Potassium chloride	326	80.5	
	OMF	BioC Nitro 16-3-2	1883	1610	1932.6
		BioC Phos 11-29-3	292	209.3	
		BioC Potasio 2-2-37	522	113.3	

Where ARE (%) is the apparent recovery efficiency, NU_f is the nutrient uptake by shoot and grain at a fertilized plot (kg ha^{-1}), NU_c is the nutrient uptake by shoot and grain at the unfertilized plot (kg ha^{-1}), and NS_a is the amount of nutrient applied through fertilization (kg ha^{-1}). Nutrient uptake (NU) was calculated by:

$$NU = NC \times B \quad (5)$$

Where NU is the nutrient uptake (kg ha^{-1}), NC is the nutrient content (%), and B is the shoot biomass or grain yield (kg ha^{-1}) (SM 2).

2.6. Life cycle analysis

Three sets of cradle-to-gate LCA were performed to assess the environmental impacts of OMF production and its use to produce maize grain at the field trials (Fig. 2). The system boundaries include raw material extraction, input transport, OMF manufacture and packaging, field application and grain harvest. Direct (*in situ*) emissions were included, while solid waste management and post-harvest processes were excluded due to their negligible contribution. Impact categories were modelled using the ReCiPe Midpoint method in SimaPro ver. 9.6 with the Ecoinvent version 3.7 and Agri-footprint version 5 databases.

Eight cradle-to-gate LCAs were conducted to assess the environmental impacts of manufacturing 50-kg bags of seven Bio-C™ OMF products and SuperSuelo™. The LCIs included raw material extraction and transport to the manufacturing plant, process energy consumption and packaging.

Four cradle-to-gate LCAs were conducted to assess the environmental impacts of producing 1 Mg of maize grain under each fertilization treatment at both trials. The LCIs included all inputs and emissions up to harvest, grouped into fertilizer, logistics (excluding crop protection products freight), water (irrigation and crop protection); manure (packed in 50-kg polypropylene bags); seed and crop protection (herbicides, insecticides, fungicides, and fuel).

2.7. Statistical analysis

SOC, grain yield, shoot biomass, AE and ARE were analyzed using analysis of variance (ANOVA). Normality and homogeneity of variance were evaluated using Shapiro-Wilk and Levene tests respectively. When the assumptions were not met, the Friedman test was applied. Treatment means were compared using Tukey's HSD following significant ANOVA results. Statistical analyses were performed using the Agricolae package (de Mendiburu, 2023), and charts were generated with ggplot2 (Wickham, 2016).

3. Results

3.1. Agronomic performance

At harvest, SOC differed significantly between OMF and control in Huaral, although no significant SOC stock differences among treatments were detected at either site. SOC stocks increased across all treatments, averaging 48 Mg ha^{-1} and 7.8 Mg ha^{-1} at Huaral and Juan Guerra respectively (Table 2). Regardless of the treatment applied, ΔSOC was positive at both sites, with consistently greater increases observed at Huaral.

Shoot biomass increased by 20% with the MF treatment at Huaral, and by 88% with OMF treatment at Juan Guerra when compared to their controls (Fig. 3). At Huaral, only the OMF treatment significantly increased grain yield by 11% compared to control. At Juan Guerra, both OMF and MF treatments significantly increased grain yield by 163% and 130%, respectively, however without significant difference between them. Agronomic efficiency was generally higher for OMF than MF at Juan Guerra (Fig. 4). For phosphorus, OMF increased agronomic efficiency by approximately 30% relative to MF and nearly 300% compared to OM, while for potassium it exceeded OM by about 300% and it was comparable to MF. Nitrogen agronomic efficiency was similar between OMF and MF, and slightly lower than OM. Apparent recovery efficiency presented a similar pattern (Fig. 5), with OMF improving phosphorus recovery by approximately 40% relative to MF and more than 500% compared to OM, and potassium recovery by nearly 40% and more than 700% respectively. At Huaral, OM presented the highest agronomic and apparent recovery efficiencies, particularly for nitrogen, however, high block variability limited statistical significance.

3.2. Fertilizer carbon footprints

The product carbon footprints for the OMF analyzed ranged from 5 to 41 kg CO_2 eq per 50-kg bag. This aligns with the reference value for OMF in Ecoinvent, with a reported range of 8.29–32.5 CO_2 eq per 50-kg bag (Moreno Ruiz et al., 2020). These OMF product carbon footprint range is much lower than those of MF, which is between 10.65 and 150 kg de CO_2 eq per 50-kg bag (Table 3). In general, Bio-C™ Nitro 16-03-02, a N-based OMF, had <30% of the product carbon footprint of ammonium nitrate, calcium nitrate, or urea based on a 50-kg bag level. BioC™ Phos 11-29-03, a P-based OMF, presented a product carbon footprint 50% smaller than those of diammonium phosphate and triple

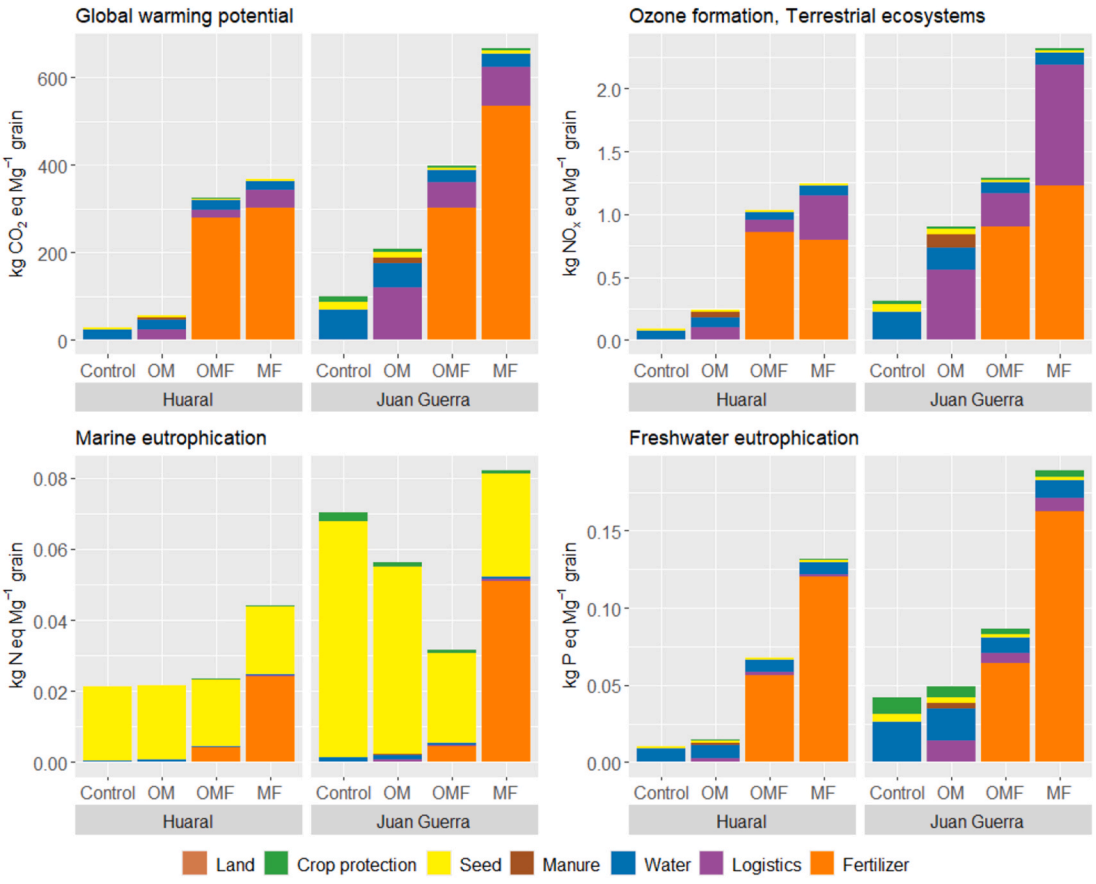

Fig. 6. C, N and P emissions to air, soil and water related to maize grain production.

superphosphate, fertilizers providing nutrient phosphorus. BioC™ Potasio 02-02-37 and BioC™ Potasio-S 01-32-31, potassium based OMF, had the smallest product carbon footprint, between 5 and 11 kg CO_2 eq per 50 kg bag, and it was similar to that of potassium sulfate. Blended MF presents a much larger CF than their BioC OMF counterparts, where higher N blends exhibit a larger CF than similar products in the same category.

3.3. Maize carbon footprint

LCA showed that OMF reduced the carbon footprint of maize production relative to MF across both trials. OMF lowered the carbon footprint per hectare by 18.2–21.8% compared to MF. When expressed per output unit, grain produced with OMF embodied 2495.5 and 2273.8 kg CO_2 eq per Mg of grain at Huaral and Juan Guerra respectively, compared with 3070.8 and 3324.9 kg CO_2 eq for MF (Table 4). Accordingly, OMF reduced the carbon footprint of grain by 44 and 271 kg CO_2 eq Mg^{-1} at Huaral and Juan Guerra respectively (Fig. 7). Differences between sites were primarily driven by fertilizer choice, although logistics contributed more at Juan Guerra, 772 km away from the manufacturing plant. CF and other impacts modelled here reflect site-level yield variability (Fig. 3), which should be considered when interpreting treatment effects.

3.4. Other environmental impacts related to maize production

Atmospheric N emissions as NOx leading to tropospheric ozone formation were lower as well for grain produced with OMF when compared to MF at both trials and N lixiviation leading to marine eutrophication is largely explained by the fertilizer choice at both locations, however, N lixiviation was largely related to seed production in all cases. P lixiviation leading to freshwater eutrophication is directly explained by the fertilizer choice as well, where the P lixiviates associated to OMF resulted close to half of those from MF at both trials. The moderate yield increments with OMF at both trials (Fig. 3) translated into a reduced pressure on mineral resources small improvements in land and water use efficiently (Fig. 7). Replacing MF with OMF also represented a reduced impact in mineral depletion at both trials since raw mineral materials are partially replaced with biogenic P and K in the OMF plans.

4. Discussion

All fertilization treatments increased the SOC stocks, yet no significant differences were found between fields treated with organic matter-based fertilizers (i.e., OM and OMF) and those treated with MF. Since SOC accumulation from organic inputs is known to be a slow and multivariate process that typically requires several years to reach significant levels, this outcome is expected (Gross and Glaser, 2021; Han et al., 2016; Mumbach et al., 2020). In tilled maize systems, where stover contributes minimally to carbon cycling, the observed SOC gains likely derive primarily from root inputs and environmental modulation of root-derived carbon deposition rather than from the fertilizers themselves (Lei et al., 2023; Shabtai et al., 2024). In seasonal crops, this new SOC can still be lost by plowing and other soil management practices as well as by intensive N application from MF (Pausch et al., 2013; Pausch and Kuzyakov, 2018). Detectable SOC increases in cropland soils generally require carbon inputs on the order of 1.4–2.6 Mg C ha^{-1} yr^{-1} to achieve annual gains of 0.1–0.4% (Bruni et al., 2022). Carbon inputs supplied in the assays were well below this range, as OMF are applied at nutrient-based rather than carbon-enrichment rates, making direct C inputs an unlikely primary driver of SOC change over a single growing

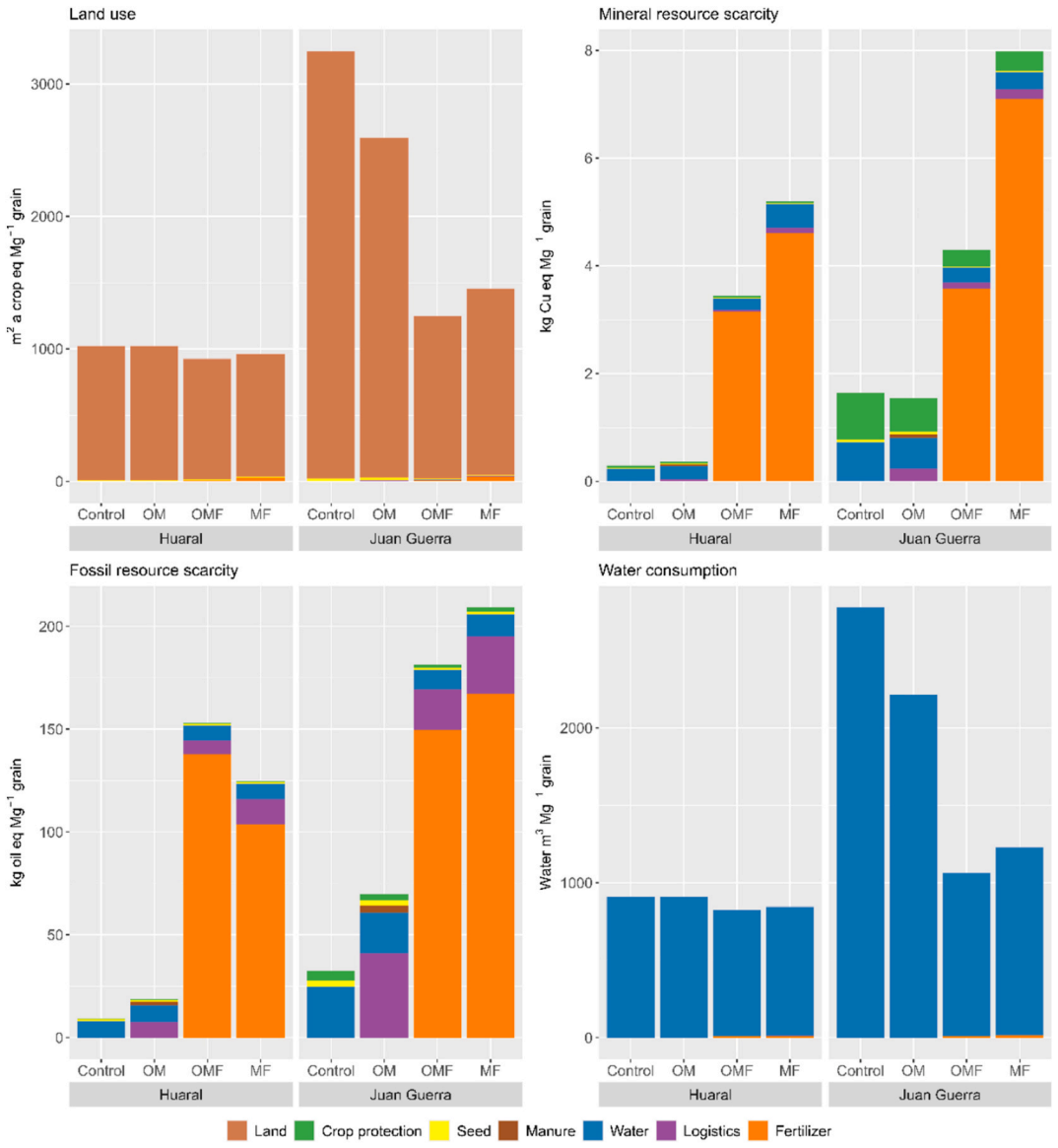

Fig. 7. Resource use efficiency in maize grain production.

season. Under these conditions, environmental processes likely dominated SOC dynamics, with cooler and drier conditions at Huaral favoring SOC retention through reduced microbial decomposition relative to Juan Guerra (Huang and Wei, 2025; Shoumik et al., 2025).

At Huaral, OMF and MF resulted in non-significant yield increases relative to the control, likely due to soil and environmental constraints. Alkaline, carbonate rich soil and extreme heat reduced nutrient availability (Barrow and Hartemink, 2023; Bolan et al., 2023), yield relative to genetic capacity (INIA, 2016) and agronomic efficiency. The lower shoot phosphorus concentration at Huaral (SM 2) is consistent with restricted phosphorus uptake from calcareous soils (Ji et al., 2025; Wang et al., 2017) and with translocation from vegetative tissues to grain (Jeong et al., 2017). Phosphorus immobilization may also reduce AE of other nutrients (Atnafu et al., 2021), and reduced ARE in maize has been previously linked to soil properties and organic fertilizers (Tamele et al., 2020). At Juan Guerra, maize reached its genetic yield potential under favorable experimental conditions. The higher nitrogen use efficiency observed has been associated with split fertilization, combined OM and MF application, and higher SOC levels (Yu et al., 2022). High biomass variability limited attribution of yield differences to MF or OMF alone (Magela et al., 2019; Mumbach et al., 2020). Consistent with previous studies, grain yields remain similar when replacing mineral N and P sources with OMF, including systems using enhanced N fertilizers (Dias et al., 2020; Frazão et al., 2021), and yield equivalence to MF has been sustained across multiple crop cycles in soybeans, maize, and other cereals (de Melo Benites et al., 2022; Mumbach et al., 2020).

The higher nitrogen agronomic efficiency observed with OMF at Juan Guerra corresponds to a reduction of 1.03 kg NOx eq Mg^{-1} grain. Agricultural NOx emissions are influenced by N application rate and rainfall and management practices can modulate these emissions (Yuttitham et al., 2020). While no-till practices may increase N_2O emissions (Pareja-Sánchez et al., 2020; Yuttitham et al., 2020), replacing MF with OMF reduced emissions in the study. Modelled freshwater eutrophication, largely driven by P leaching was also reduced under OMF, consistent with slower nutrient mineralization and reduced P mobilization (Bian et al., 2022; Bonsdorff, 2021; Hua and Zhu, 2020; Tejada et al., 2005; W. Zhang et al., 2018). These processes contribute to improved soil quality over time (Liu et al., 2021; Smith et al., 2020). Maize CF often exceed 1 Mg CO_2 eq Mg^{-1} grain (Yao et al., 2021), nearly double the values reported here. Replacing MF with OMF reduced CF by up to 232 kg CO_2 eq Mg^{-1} grain, exceeding the 177 kg CO_2 eq Mg^{-1} grain reduction previously reported with OMF (W. Zhang et al., 2018)

and highlighting its decarbonization potential in value chains consuming maize. This CF reduction largely reflects processes in the fertilizer supply chains, with transport distance and modality playing a major role, as illustrated by the differences between Huaral and Juan Guerra (Inkinen and Hämäläinen, 2020; Nusa and Kodak, 2023), 290 and 1695 km away from the plant respectively (Fig. 6, SM 3). Optmizing spatial integration between livestock and crop systems is therefore critical for achieving the sustainability of manure-based OMF (Rosa and Gabrielli, 2023).

Because maize is a major livestock feed, cleaner grain production can substantially increase food systems sustainability. In Peru, maize-related emissions contribute significantly to poultry-based diets, suggesting that large-scale adoption of OMF could deliver meaningful system-level emission reductions (Arrieta and González, 2019; Noya et al., 2016). In Peru, chicken meat account for approximately 16% of the diet-related GHG emissions, of which 20% is contributed by maize-based feed. These links highlight the potential for OMF to deliver benefits beyond the filed scale (Vázquez-Rowe et al., 2019). Future research should evaluate the system-wide impacts of OMF adoption in Peruvian food systems, including regional deployment scenarios, integration between livestock and crop sectors, and the implications for emissions mitigation at both industrial and community scales.

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CRediT authorship contribution statement

Tomás Samaniego: Investigation, Methodology, Writing – original draft. **Yuri G. Arévalo-Aranda:** Investigation. **Wendy E. Pérez:** Investigation. **Fernando Chung-Montoya:** Formal analysis, Investigation, Supervision, Writing – original draft. **Laura Gómez Palomino:** Data curation, Formal analysis, Investigation. **Flor Quispe Callasi:** Data curation, Formal analysis, Investigation. **Berlan Rodríguez Pérez:** Formal analysis, Methodology, Software. **Fang Jia:** Conceptualization, Resources, Supervision. **Jorge Achata Böttger:** Conceptualization, Data curation, Funding acquisition, Methodology, Writing – original draft.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2026.100460.

Data availability

Data will be made available on request.

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