



Integrative Approaches to Enhance Soil Quality and Crop Performance Through Residue Management and Nitrogen Fertilization in Diverse Cropping Rotations

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Abstract

This study investigates the impact of wheat residue management and nitrogen (N) fertilization on soil properties and crop yields in wheat-maize and wheat-mungbean cropping systems. The research aims to determine the influence of different levels of residue retention and N application influence soil organic carbon, nutrient content, available water, and aggregate stability, crop performance. Field experiments were conducted during two growing seasons in the Shabab region (Iran). Three wheat residue management methods (no removal, 50% removal, and 100% removal) and four N fertilization rates (100%, 50%, 25%, and 0% of the conventional application) were evaluated. Soil properties and crop yields were assessed, and Principal Component Analysis (PCA) was used to determine the relationships between treatments and soil health indicators. PCA demonstrated a strong model fit (KMO=0.919, $R^2=0.987$), explaining 83% of the total variance in soil quality. Mungbean systems significantly increased soil nutrient levels ($p<0.01$) compared with maize. Residue retention and higher N levels improved the soil structure and fertility. Full wheat residue retention combined with optimal N fertilization enhanced biological and grain yields, with models explaining 98.2% and 94.4% variance, respectively, 97.8% for maize and 84.2% for mungbean. Significant crop system×residue interactions ($p=0.012$) underscore integrated management importance for sustainable productivity. Integrating crop residue management with appropriate N fertilization enhances soil health and crop productivity. These findings highlight the importance of sustainable soil fertility management practices to promote long-term agricultural sustainability while mitigating environmental risks.

Keywords Sustainable agriculture · Soil security · Environmental pollution · Agroecosystem management

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1 Introduction

Globally, soil resources face increasing scarcity for agricultural use, necessitating sustainable management strategies to address food security and environmental concerns (Rockström et al. 2017). The European Union has prioritized soil health and food security in its research and innovation programs, recognizing its fundamental importance for sustainable development (Lal et al. 2021). Healthy soils provide several ecosystem services, including carbon sequestration, biodiversity support, water retention, reduction of greenhouse gas emissions, pollutant detoxification, nutrient supply, and food production. These services are essential for advancing sustainable development goals (SDGs) (Bouma 2014; Veerman et al. 2020; Rodrigo-Comino et al. 2020). However, intensive agricultural production systems increasingly compromise these soil functions through detrimental management practices, whereas climate change further exacerbates degradation processes (Lal 2013; Deng et al. 2021; Szilassi et al. 2022). Additionally, the excessive removal of crop residues for animal feed and industrial use has led to negative effects such as soil organic matter depletion, nutrient loss, erosion, and reduced crop productivity (Rahdari et al. 2023; Ruis et al. 2018; Rodrigo-Comino et al. 2018; Sarkar et al. 2020; Parlak et al. 2022).

To prevent the degradation of agricultural soil functions, it is critical to maintain soil fertility and productivity to achieve sustainable agricultural production (Suleymanov et al. 2021). Adopting climate-resilient agricultural practices is essential for both climate adaptation and mitigation efforts, as well as for developing sustainable and secure food systems (Lal 2016; Rumpel et al. 2020). These impacts are particularly concerned with the role of the soil as the largest terrestrial carbon reservoir, highlighting the critical importance of sustainable soil management practices for both climate change mitigation and adaptation (Esmailian et al. 2023; Smith 2016). Thus, the development of climate-resilient agricultural practices has become essential for establishing sustainable and secure food systems capable of withstanding environmental pressures (Lal 2016; Rumpel et al. 2020).

The management of crop residues, which involves handling plant remains post-harvest, is crucial for enhancing soil quality and fertility, and plays a significant role in mitigating greenhouse gas emissions (Johnson et al. 2017; Stewart et al. 2015). FAO's voluntary guidelines for sustainable soil management also emphasize the importance of effective crop residue management (FAO 2017). Crop residue management (CRM) is a pivotal intervention strategy for enhancing soil quality and fertility while contributing to greenhouse gas mitigation (Johnson et al. 2017; Stewart et al. 2015). Indeed, CRM can yield benefits at multiple levels:

(i) at the farm scale, retaining crop residues enriches the soil with organic carbon and nutrients, improving soil fertility and structure; (ii) at the regional level, CRM enhances groundwater reserves by reducing runoff and promoting soil infiltration; and (iii) at the global level, CRM contributes to carbon sequestration, helping to mitigate greenhouse gas emissions and combat global warming (Rasool et al. 2020; Ravindra et al. 2019; Sarkar et al. 2020; Zhang et al. 2021; Amankulova et al. 2023). The sustainable management of crop residues to ensure soil quality and yield production depends on various site-specific factors, including residue quantity, soil properties, agricultural practices, and cropping systems. Previous studies have suggested associations between higher residue removal rates and deteriorating soil quality indicators, including reduced organic matter content and compromised crop performance (Blanco-Canqui et al. 2006; Al-Shammmary et al. 2023; Sindelar 2012). These factors vary across climates, regions, and management strategies, necessitating evaluation on a smaller scale (Blanco-Canqui et al. 2014; Lozano-Parra et al. 2023). Additionally, the sustainable removal of crop residues requires a holistic understanding of site-specific factors, including residue quantity, soil characteristics, and agricultural practices, which vary significantly across regions and management approaches (Clay et al. 2019).

Conversely, overapplication of mineral nitrogen (N) fertilizers to maximize crop yields poses several environmental risks, including soil salinization, acidification, and pollution within agroecosystems (Beaudoin et al. 2005; Shi et al. 2009). The N fertilization rates also influence soil organic matter dynamics, affecting biomass decomposition and carbon mineralization processes (Guzman and Al-Kaisi 2014; Van Vleck and King 2011). Integrating N fertilizers with crop residue return can boost soil microbial activity and residue decomposition (Fu et al. 2021a, b). The sustainability of these practices is influenced by cropping system, soil type, and climatic conditions (Guzman and Al-Kaisi 2014; Mu et al. 2008). Higher residue removal rates have been associated with lower soil organic matter content and reduced crop performance (Blanco-Canqui et al. 2006; Al-Shammmary et al. 2023; Sindelar 2012).

Despite the recognized importance of soil health and fertility in sustainable agriculture, there remains a critical knowledge gap regarding the interactive effects of crop residue management and N fertilization across different cropping systems (Fu et al. 2021a, b). Although previous studies have examined crop residue management and N application independently, comprehensive research quantifying their combined effects on soil properties and crop productivity in wheat-based rotation systems is limited. Specifically, there is insufficient understanding of how varying levels of wheat residue retention (complete retention, partial retention, or

removal) interact with different N fertilization rates to influence soil nutrient dynamics and yield outcomes in maize and mungbean cropping systems. This gap is particularly pronounced in semi-arid regions, where residue management decisions are often driven by competing demands for animal feed versus soil improvement, necessitating evidence-based recommendations that optimize both productivity and sustainability outcomes. Existing studies highlight the adverse effects of excessive residue removal on soil quality, soil health, crop productivity, and greenhouse gas emissions (Liska et al. 2014; Turmel et al. 2015; Battaglia et al. 2021). Furthermore, while integrating N fertilizers with crop residue return shows promise in enhancing soil microbial activity and residue decomposition, more targeted investigations are needed to assess the sustainability of these practices in different agroecological contexts. The potential synergistic or antagonistic effects of combining residue management with N fertilization also require further exploration to optimize soil health, yield production, and environmental outcomes (Li et al. 2021; Hu et al. 2023). This study hypothesized that: (i) retaining wheat (*Triticum aestivum* L.) residue would significantly improve soil organic carbon, nutrient availability, and aggregate stability compared to residue removal; (ii) the positive effects of residue retention would be most pronounced when combined with moderate nitrogen fertilization rates (50–75% of conventional); and (iii) complete residue removal would result in significant soil quality degradation, regardless of N fertilization level. To test these hypotheses, the objectives were: (i) to assess how the removal of wheat residues and different N fertilization rates, along with their combined effects, influence soil properties in wheat-maize (*Zea mays*) and wheat-mung bean (*Vigna radiata*) cropping systems; (ii) to evaluate the impact of these factors on the yield of maize and mung bean; and (iii) to determine the sustainable threshold for removing crop residues under these crop rotations.

2 Materials and methods

2.1 Experimental Sites and Treatments

A two-year field experiment was conducted during the 2019 and 2020 growing seasons in the Shabab region of Western Iran (33°44' N, 46°38' E, 982 m a.s.l.). The experimental area is characterized by a semi-arid environment with 11.8 °C average air temperature and a total rainfall of 422 mm. The soil was classified as silt loam texture with the following characteristics: sand (18%), silt (60%), clay (22%) content, pH (7.2), total N content (0.05%), organic carbon content (0.5%), bulk density (1.46 g cm⁻³), respectively. Typical crop rotations in the experimental area used

to include wheat–maize and wheat–mungbean, both subjected to conventional tillage practices. Two adjacent fields, representing these crop rotations, were selected for the study. In each experimental field, the following experimental treatments were applied: (i) three wheat residue-management based on different removal rates [no removal (WR1), removal of 50% of wheat residues (WR2), and removal of 100% of wheat residues (WR3)], and (ii) four N fertilization rates based on local agronomic recommendations and soil testing results: [(a) N1: 100% of the conventional N application (120 kg N ha⁻¹ for maize, 30 kg N ha⁻¹ for mungbean) determined from regional extension guidelines and soil N analysis indicating baseline fertility levels; (b) N2: 50% of the conventional N application (60 kg N ha⁻¹ for maize, 15 kg N ha⁻¹ for mungbean) designed to evaluate reduced input scenarios; (c) N3: 25% of the conventional N application (30 kg N ha⁻¹ for maize, 7.5 kg N ha⁻¹ for mungbean) representing minimal fertilization; and (d) N4: 0% of the conventional N application (control treatment)]. The conventional rates were established based on the regional agricultural extension service, considering typical farmer practices in the study region.

Total N fertilization in the experimental area was applied at rates of 138 and 30 kg ha⁻¹ for maize and mungbean, respectively, using urea fertilizer. The experiment comprised of 84 plots per year (48 plots per crop rotation), with each basic plot measuring 150 m² (10 × 15 m). A split-plot experimental design was employed with four replications, where the main plots were randomly assigned to crop systems (maize and mungbean), and the sub-plots were randomly allocated to treatment combinations of N levels and wheat residue levels within each main plot. The randomization of plots was conducted using a random number generator to ensure unbiased treatment allocation and minimize systematic errors across the experimental area.

2.2 Treatments, performing, and Planting Operations

In both experimental growing seasons, the field trials commenced on June 25, 2019, and June 22, 2020, following wheat harvesting and determination of wheat residue amounts. Wheat residue weight was determined using wooden frames (1 m × 1 m) randomly placed four times in the experimental area within each experimental plot. Fresh wheat residues were collected from within each frame immediately after harvest, weighed, and then converted to per hectare basis, which averaged 4.5 Mg ha⁻¹. For residue management treatments, WR1 (100% retention) involved leaving all wheat residues uniformly distributed on the soil surface, WR2 (50% retention) required manual removal of half of the residues by weight from each plot using rakes

and collection bags, and WR3 (complete removal) involved thorough removal of all visible wheat residues from the plot surface. The retained residues were chopped into 5–10 cm lengths using a mechanical chopper and incorporated into the top 15 cm of the soil through shallow tillage operations before sowing the subsequent crops.

This procedure was repeated for both experimental periods. In all residue-management treatments, wheat straw was finely chopped and incorporated into the soil up to a depth of 30 cm using plowing.

The N fertilization was carried out in two stages: (i) at sowing, 50% of the total N rate was applied according to experimental treatments, and (ii) the remaining N fertilizer was applied one month after seedling emergence for both maize and mungbean crops.

Urea fertilizer was uniformly distributed in the soil during both treatments. Maize and mungbean were sown at seed densities of 8 seeds per m² and 24 seeds per m², respectively. Irrigation schedules were adapted to environmental conditions and were typically performed every 10–12 days, following local farming practices.

Crop yields were assessed on October 18, 2019, and October 15, 2020, for the first and second years, respectively.

2.3 Measurement of Soil Properties and Crop Yield

Total biomass was quantified by manual harvesting and weighing of the entire plot. Post-threshing, grain, and straw yields for each plot were weighed separately and expressed in tons per hectare. Soil sampling was conducted on October 16, 2020, following a two-year experimental period. Samples were collected from a depth of 0–30 cm at six random locations within each plot and combined to form a homogeneous sample. These samples were air-dried, sieved through a 2 mm mesh, and divided into two parts. Soil organic carbon (OC) and total nitrogen (TN) were determined via the Wet Oxidation (Walkley and Black 1934) and the Kjeldahl methods (Bremner 1996), respectively. Available potassium (Available K) and phosphorus (Available P) were quantified using Ammonium Acetate Extraction-Flame Photometry (Knudsen et al. 1982) and NaHCO₃ Extraction-Colorimetric methods, respectively. Micronutrients (Fe, Cu, Zn, and Mn) were measured in the DTPA extracts using atomic absorption spectrophotometry (Lindsay and Norvell 1978). Soil physical properties: Soil available water (Aw) was calculated from the moisture content difference between the field capacity (FC) and permanent wilting point (PWP) (Cassel and Nielsen 1986). Moisture retention at FC and PWP were determined at 0.3 bar and 15 bar, respectively, using a pressure plate apparatus. Water-stable aggregates (WSA) was assessed using the wet sieving method (Kemper and Rosenau 1986).

2.4 Statistical Analysis

The normal distribution of variables was assessed using the Shapiro-Wilk test. For multiple comparisons, a robust heteroscedastic one-way analysis of variance (ANOVA) for the trimmed mean (20% trimming level) was applied. Yuen's test (20% trimming level) was used for two-group comparisons and post-hoc analysis. These tests were conducted in R version 4.3.2 (R Core Team 2023) using the WRS2 package version 1.1-4 (Mair and Wilcox 2020) and ggstatsplot package version 0.11.1 (Patil 2021). Additional statistical analyses were performed using the stats package (base R) for ANOVA, the psych package version 2.3.9 for Principal Component Analysis, and the ggplot2 package version 3.4.4 for data visualization. A standardized Principal Component Analysis (PCA) was performed using a correlation matrix with input variables including OC, TN, Mg, Fe, Mn, AW, K, WSA, Ca, Cu, and P. Zn was excluded due to its unique properties. PCA is a technique used to reduce the number of variables and eliminate the interrelationships among them by developing a set of new variables (principal components, PCs). These variables were chosen to sufficiently explain the variation in the data.

The number of PCs was determined based on Kaiser's rule, and the model fit was assessed using the Root Mean Square Error (RMSR) and Kaiser-Meyer-Olkin (KMO) test for sampling adequacy. General Linear Modeling (GLM) was used to explore the differences in PC scores by CropS, WRL, and NL. Assumptions were validated using Shapiro-Wilk and Levene tests. The tested hypotheses included the equality of treatment effects across crop systems and the absence of interactions among factors. The effect size (η^2p) was calculated for each factor. Yield data were analyzed by crop system and yield type (biological, grain, and straw) using separate GLMs for each evaluating factor interaction. The role of the 'Year' in the dataset was also assessed.

3 Results

3.1 Soil Properties

Principal Component Analysis (PCA) yielded a highly satisfactory fit, as indicated by a KMO measure of sampling adequacy of 0.919 and an RMSR of 0.05. The model accounted for 83% of the total variance with one principal component (PC). The subsequent General Linear Model (GLM) analysis of this PC revealed a strong relationship ($R^2 = 0.987$) with the crop system (CropS), nitrogen level (NL), and wheat residue level (WRL). All the individual factors were significant contributors to the model. Notably, the interaction between CropS and WRL was significant ($p = 0.012$), indicating that the effect of residue management on soil properties varied between

crop systems. This differential response suggests that maize systems benefit more substantially from residue retention, possibly because of the crop's higher carbon demand and greater root biomass production, whereas mungbean's nitrogen-fixing capability and lower residue production created less pronounced residue management effects on soil properties. Although the interactions between CropS $\times$ NL and WRL $\times$ NL were not statistically significant, they exhibited medium effect sizes, suggesting a moderate influence of these interactions on the soil properties. The three-way interaction between CropS, NL, and WRL demonstrated only a small effect (Table 1; Fig. 1). The moderate CropS $\times$ NL interaction suggests that maize systems responded more strongly to nitrogen fertilization when combined with residue retention, likely due to maize's higher nitrogen demand and greater biomass production compared to mungbean's biological nitrogen fixation capability. The WRL $\times$ NL interaction indicated that nitrogen fertilizer efficiency was enhanced under higher residue retention levels, possibly due to improved nitrogen retention through enhanced soil organic matter and reduced leaching losses. These interactions are agronomically important because they suggest that residue management strategies should be tailored to specific crop systems: maize systems may require higher nitrogen inputs to fully capitalize on residue benefits, whereas mungbean systems can achieve similar productivity gains with lower nitrogen rates because of their inherent nitrogen-fixing capacity and more efficient nutrient utilization under residue-enriched conditions.

Soil nutrients, including total nitrogen (TN), phosphorus (P), potassium (K), iron (Fe), manganese (Mn), as well as available water (AW) and water-stable aggregates (WSA), were significantly higher ($p < 0.01$) under the mungbean cropping system than in maize (Figs. 2 and S1). Notably, mungbean systems showed 22% greater improvements in

WSA under residue retention than maize systems, potentially attributed to differences in residue decomposition rates and root exudate composition. Mungbean's fibrous root system and nitrogen-rich root exudates likely enhance microbial activity and promote faster incorporation of organic compounds into soil aggregates. Additionally, the lower C:N ratio of mungbean residues (18:1) compared with wheat residues (45:1) may facilitate more rapid decomposition and humification processes, leading to enhanced aggregate stability. The symbiotic relationship between mungbean and rhizobia bacteria also contributes additional organic compounds and extracellular polysaccharides that act as binding agents for soil particles, further explaining the superior WSA formation in mungbean systems. Magnesium (Mg) was significantly higher at $P < 0.05$. Significant increases ($p < 0.01$) in these parameters and organic carbon (OC) were observed in WR1 and WR2 compared to WR3 (Figs. 3 and S2). Additionally, all studied soil parameters (except OC, P, Mn, and AW) were significantly ($p < 0.01$) affected by NL, with N1 resulting in significant increases compared to the other levels (Figs. 4 and S3). These results indicate that soil properties are significantly influenced by the type of crop system, the level of nitrogen fertilization, and the extent of wheat residue management, with some interactions between these factors affecting the outcomes.

3.2 Crop Yield

3.2.1 Maize Yield

Biological and grain yields were significantly different (Table S1). The GLM for biological yield accounted for 98.2% of the variance (adjusted R^2), with all the factors (year, WRL, and NL) being significant (Table S2). The interaction between year and NL was also significant, indicating very strong effects on biological yield. Although other interactions were not statistically significant, they showed weak effects. When 'Year' was excluded from the model, the results still indicated significance ($F = 6.9$, $df = 11$, $p < 0.001$), but the adjusted R^2 decreased to 0.406. In this scenario, only the effect of the WRL remained significant.

For grain yield, the model was also significant, explaining 94.4% of the variance (adjusted R^2). All factors (WRL, NL, Year) and most interactions, except for the triple interaction (WRL $\times$ NL $\times$ Year), were significant, showing at least moderate effects. The influence of 'Year' on grain yield was slightly less pronounced than that on biological yield (Table S3). Excluding 'Year' from the grain yield model resulted in an adjusted R^2 of 0.768 ($F = 29.59$, $df = 11$, $p < 0.001$), indicating a substantial reduction in explanatory power. However, the model remained significant, highlighting the importance of WRL and NL on maize grain yields.

Table 1 Summary of the general linear model (GLM) performed on the principal component scores

Factors	SS	df	F	<i>p</i>	η^2p
Model	92.76	23	231.31	<0.001	0.98
CropS	11.68	1	669.91	<0.001	0.90
WRL	66.17	2	1897.53	<0.001	0.98
NL	14.03	3	268.33	<0.001	0.91
CropS $\times$ WRL	0.16	2	4.67	0.012	0.11
CropS $\times$ NL	0.08	3	1.56	0.20	0.06
WRL $\times$ NL	0.07	6	0.74	0.61	0.06
CropS $\times$ WRL $\times$ NL	0.025	6	0.24	0.96	0.02
Residuals	1.23	71			
Total	94.00	94			

CropS Crop system (Maize vs. Mungbean), *WRL* Wheat residue level (WR1: no removal, WR2: 50% removal, WR3: 100% removal), *NL* Nitrogen level (N1: 100%, N2: 50%, N3: 25%, N4: 0% of conventional application), *SS* Sum of Squares, *df* degrees of freedom, *FF*-statistic, *p* significance level, η^2p partial Eta squared effect size. Bold values indicate statistical significance ($p < 0.05$)

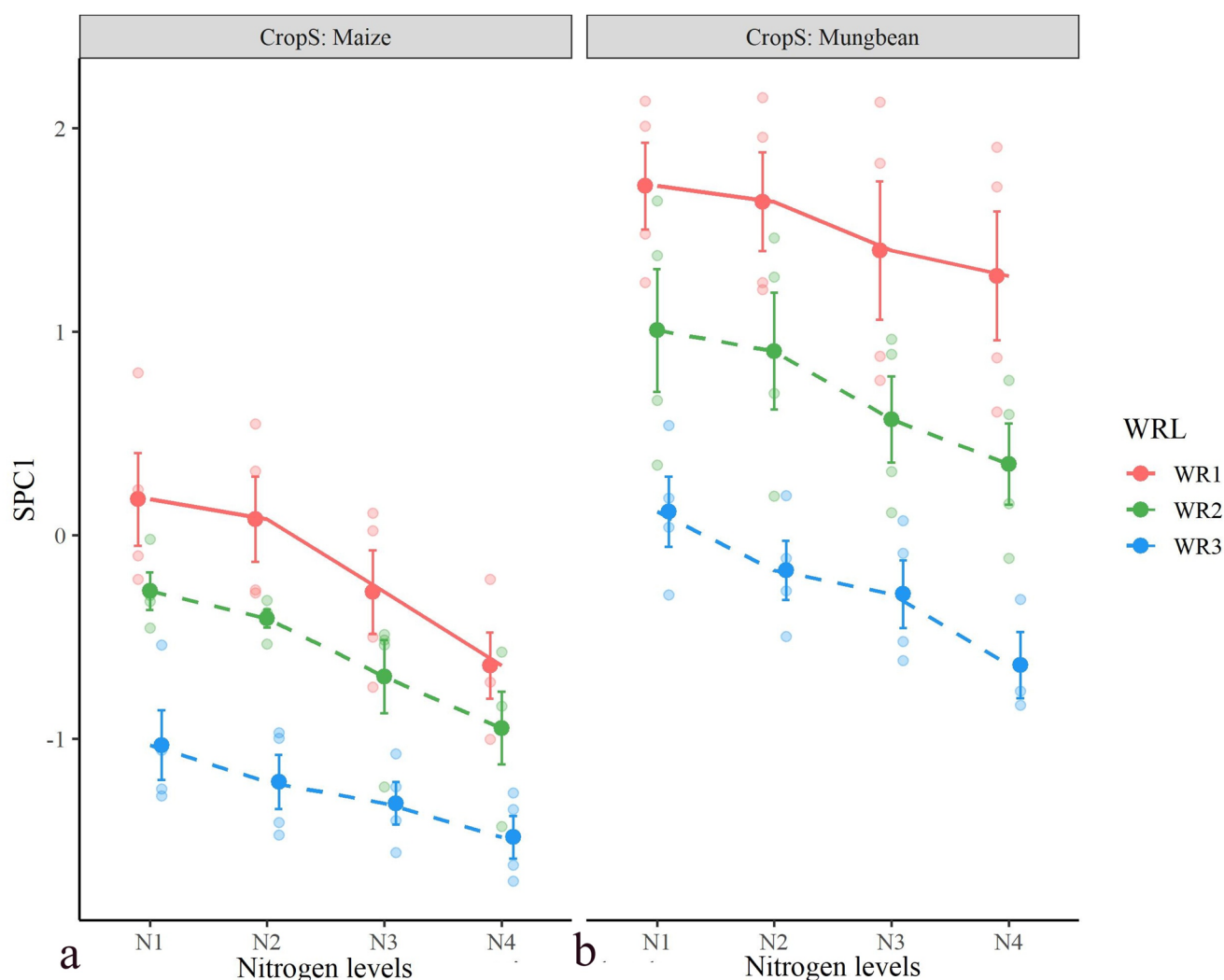


Fig. 1 Medians of the first Principal Components (SPC1 where 'S' refers to the standardized PCA) by the Crops Systems (CropS), Nitrogen Level (NL), and Wheat Residue Levels (WRL)

The biological and grain yields of maize in 2020 were significantly higher than those in 2019. The WR1 and N1 treatments resulted in the greatest increase in yield among all the treatments (Figure S4). The presence of significant interactions, especially between Year and NL, underscores the importance of considering temporal variations in managing residue levels and nitrogen application. The results demonstrated that residue management and nitrogen fertilization are critical factors for optimizing maize yield, with their effects being modulated by annual climatic and environmental conditions.

3.2.2 Mungbean Yield

Yearly differences were not significant for mungbean biological yield but were significant for grain yield (Table S4). The GLM for biological yield explained 97.8% of the

variance (adjusted R^2), with all factors - Year, WRL, and NL - being significant (Table S5). Among the interactions, only the Year $\times$ WRL interaction was significant, indicating a strong effect. Although the interactions of Year $\times$ NL and WRL $\times$ NL were not statistically significant, they exhibited medium effects. Omitting 'Year' from the model had a negligible impact, reducing the adjusted R^2 by only 1.3%.

The GLM for grain yield accounted for 84.2% of the variance (adjusted R^2). Yearly differences in grain yield were significant (Table S4), with all factors being significant. The interaction between Year $\times$ WRL was significant and exhibited large effects (Table S6). Other interactions had small or negligible effects. When 'Year' was excluded from the model, the adjusted R^2 decreased to 0.462, but WRL and NL remained significant, displaying medium and large effects, respectively.

In summary, for mungbean, biological yield was primarily influenced by WRL and NL, with the Year $\times$ WRL

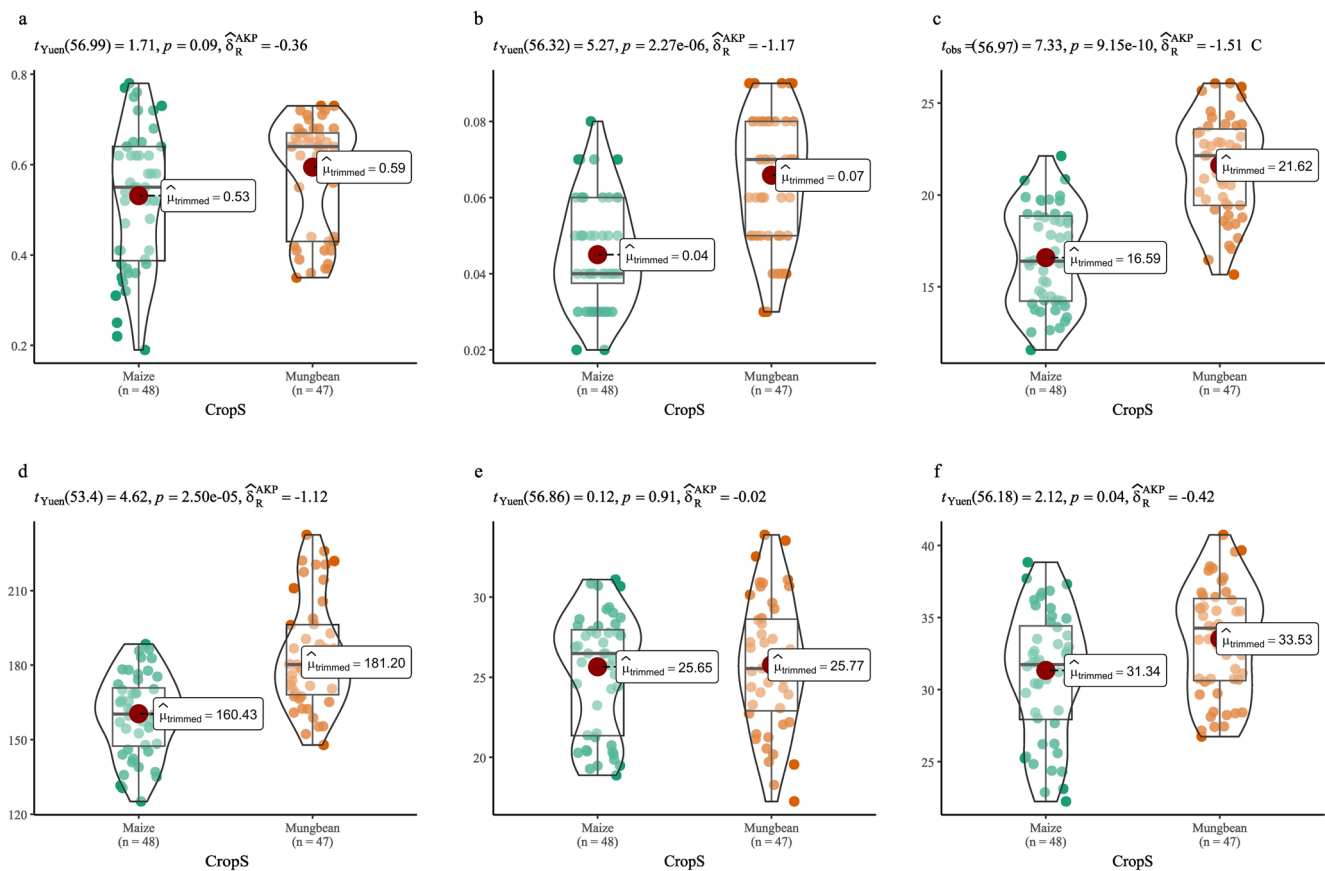


Fig. 2 Violin plots associated with boxplots reporting the distribution of soil chemical properties by the cultivation of maize and mung bean crops (a: OC (Organic Carbon), b: TN (Total Nitrogen), c: P (Phos-

phorus), d: K (Potassium), e: Ca (Calcium), f: Mg (Magnesium); red point: trimmed mean of each soil chemical parameter; n: the number of measurements; ξ : effect size)

interaction being the most significant among the interactions. Grain yield was significantly affected by Year, WRL, and NL, with the Year $\times$ WRL interaction showing a strong effect. In 2020, both biological and grain yields of mungbean were significantly higher than those in 2019, with the WR1 and N1 treatments showing the largest increases in yields compared to other treatments (Fig. 5).

Removing 'Year' from the models highlighted the persistent significance of WRL and NL in both biological and grain yields, although the overall explanatory power was reduced, particularly for grain yield. These findings suggest that residue management and nitrogen application are critical for optimizing mungbean yield, with their effects varying across different years.

4 Discussion

This study revealed significant interactions among crop systems (CropS), nitrogen levels (NL), and wheat residue levels (WRL) in influencing soil properties and crop yields. Notably, there was a significant direct relationship

between CropS and WRL ($p=0.012$). This finding highlights that residue management is not a uniform practice but a system-dependent process, where crop sequence, residue quality, and nutrient dynamics interact to determine soil functionality. Our results support the hypothesis that crop residue management effects vary significantly among different cropping systems, as evidenced by the significant CropS $\times$ WRL interaction. Returning crop residues to the soil enhances soil aggregate stability by adding fresh organic matter, which increases the proportion of humus and improves the aggregate structure and microbial activity of the soil (Blanco-Canqui and Lal 2008). Previous studies have shown that crop residue incorporation enhances various biological, physical, and chemical qualities of soil, preserves soil moisture, and boosts crop yield (Hejazi et al. 2010). Mechanistically, these improvements are driven by the decomposition of residues that release labile carbon, stimulating microbial biomass and enzymatic activity, which in turn improve soil aggregation and nutrient cycling. Preservation of residue also shields the topsoil and lowers soil nutrient loss (Mandal et al. 2019). The enhancement of soil aggregate stability through residue retention operates

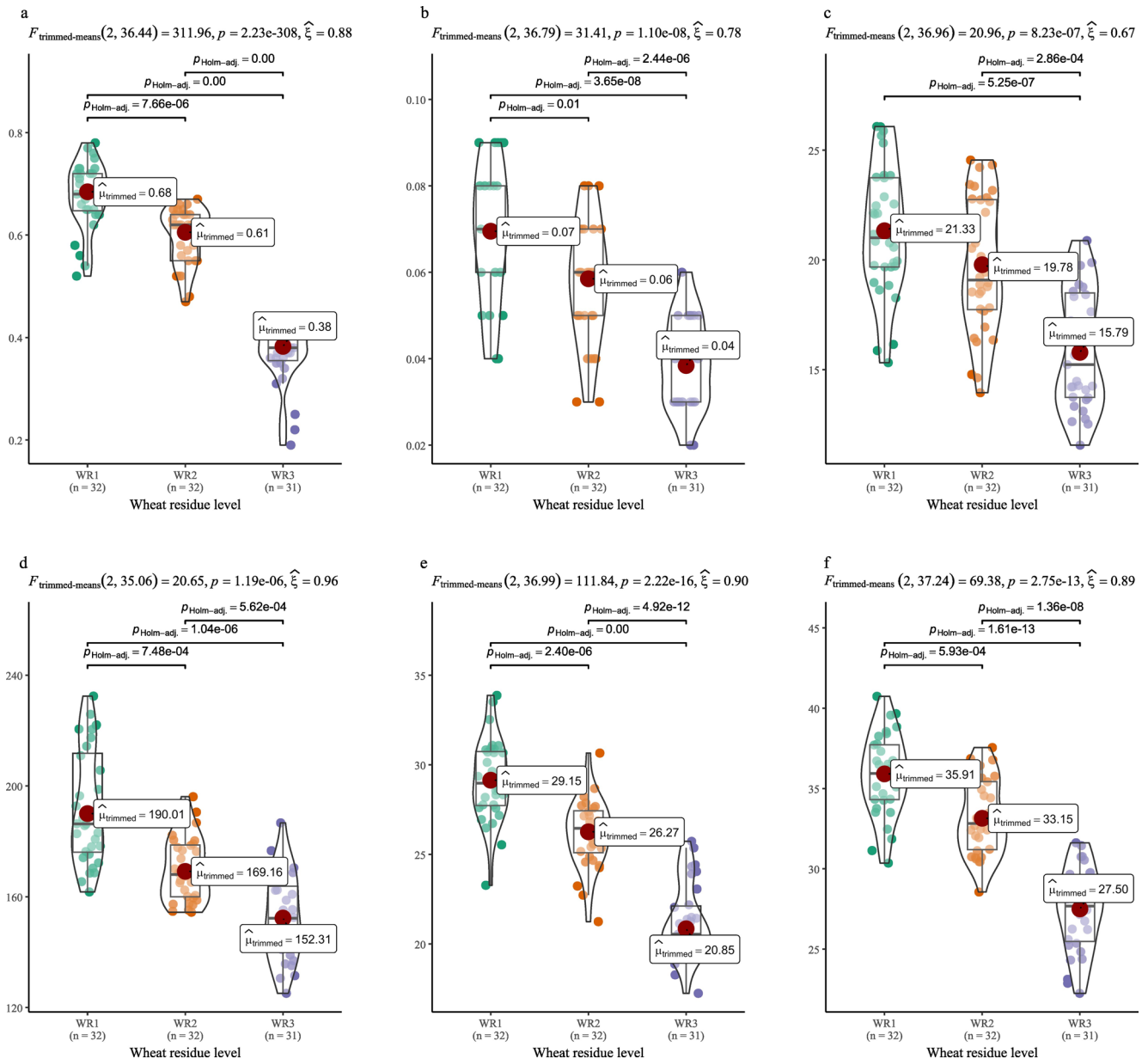


Fig. 3 Violin plots associated with boxplots reporting the distribution of soil chemical properties by different wheat residue (WR) managements (**a**: OC (Organic Carbon), **b**: TN (Total Nitrogen), **c**: P (Phos-

phorus), **d**: K (Potassium), **e**: Ca (Calcium), **f**: Mg (Magnesium); red point: trimmed mean of each soil chemical parameter; n: the number of measurements; ξ : effect size)

through multiple biological mechanisms. Fresh organic matter inputs stimulate microbial communities to produce extracellular polysaccharides and other binding agents that act as ‘glues’ between soil particles (Six et al. 2004). Additionally, fungal hyphae proliferate in response to carbon-rich substrates, creating physical networks that enmesh the soil particles. These combined biological and physical processes explain the improved soil structure observed in residue-retaining treatments, confirming that soil aggregation is a biologically mediated process rather than a mere physical

effect of residue cover. The interaction between root exudates from growing crops and decomposing residues creates hotspots of microbial activity, further enhancing aggregate formation through the production of microbial metabolites and necromass (Lehmann et al. 2017). Overall, this mechanism-based interpretation provides the rationale behind the observed synergy between the cropping system and residue management.

The addition of crop residues is known to enhance soil content of N, P, K, and soil organic matter (SOM) (Mandal

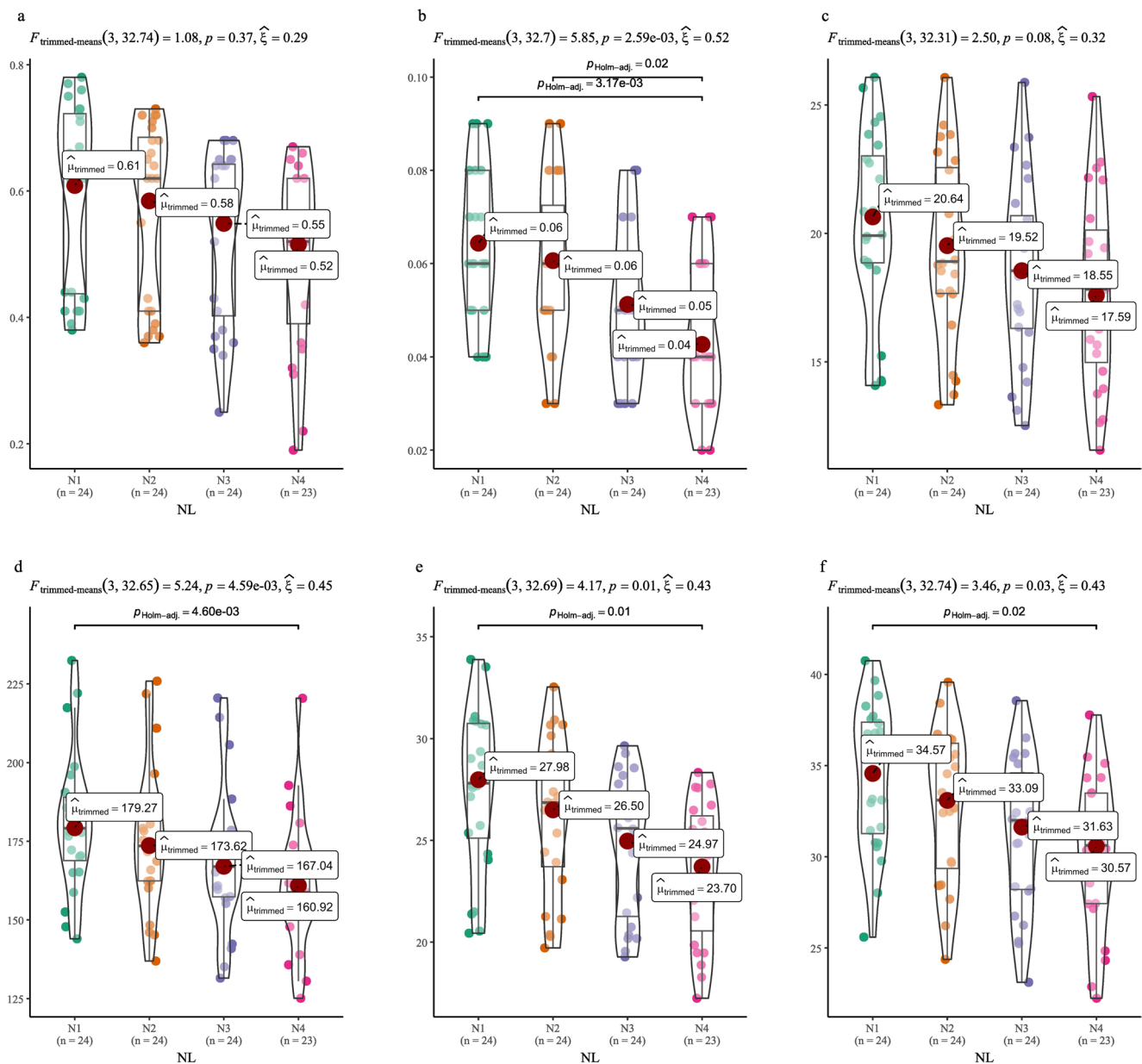


Fig. 4 Violin plots associated with boxplots reporting the distribution of soil chemical properties by different nitrogen levels (N1-N4; **a**: OC (Organic Carbon), **b**: TN (Total Nitrogen), **c**: P (Phosphorus), **d**: K

(Potassium), **e**: Ca (Calcium), **f**: Mg (Magnesium); red point: trimmed mean of each soil chemical parameter; n: the number of measurements; $\hat{\xi}$: effect size)

et al. 2019). Furthermore, residue retention and incorporation improve the availability of nutrients to plants, positively affecting the nitrogen concentration and uptake by grains (Gupta and Gandhi 2023). In our experiment, this translated into higher nutrient availability under integrated residue and nitrogen management, supporting the concept of nutrient recycling and synchronization between residue mineralization and plant uptake. Our findings confirm the hypothesis that integrated residue and nitrogen management significantly enhance nutrient availability, as demonstrated

by the superior soil nutrient status under combined treatments. This study confirms that crop residue management practices and nitrogen levels significantly impact nutrient uptake by grains (Gupta and Gandhi 2023). These results underscore the importance of balancing nutrient inputs from residues and fertilizers to maintain soil fertility while avoiding nutrient depletion or excessive nitrogen application.

However, the interactions between CropS $\times$ NL and WRL $\times$ NL were found to be non-significant in this study. Contrary to our initial hypothesis, the synergistic effects of

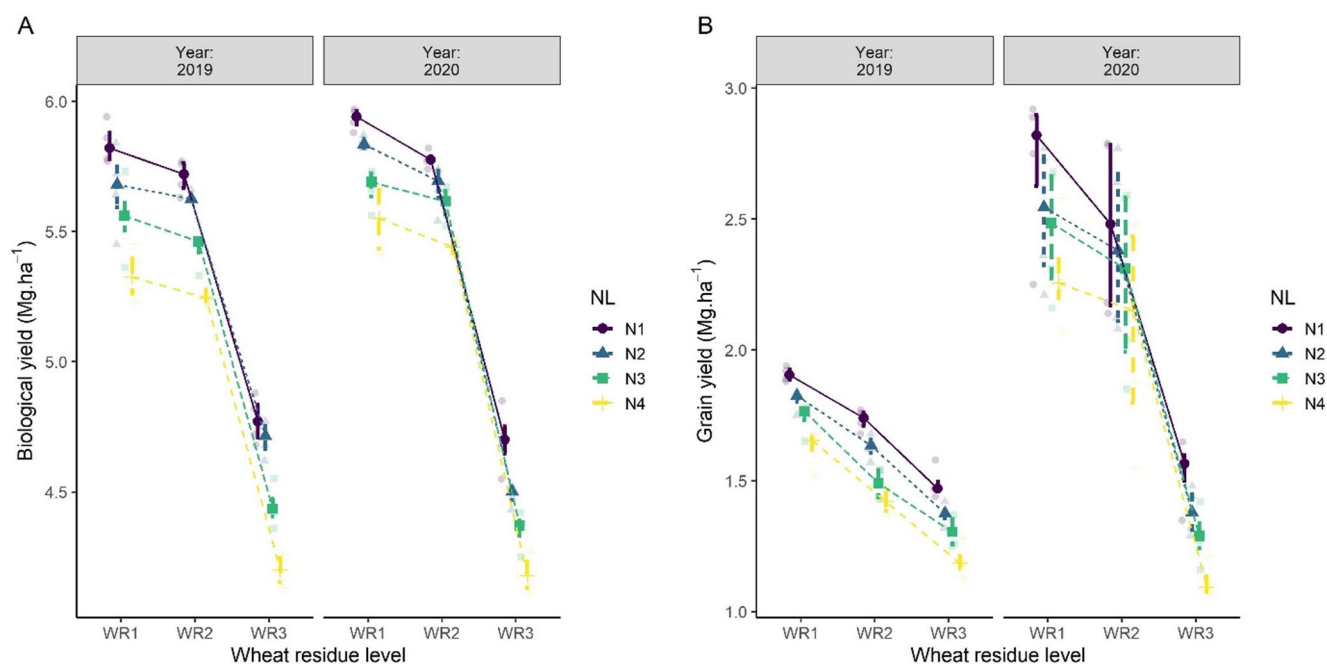


Fig. 5 Medians and quartiles of mung bean biological yield (**A**) and grain yield (**B**) by wheat residue level and nitrogen levels (NL). Data averaged over 2019 and 2020 growing seasons. Vertical bars indicate standard errors

nitrogen fertilization and residue management were less pronounced than expected, although medium effect sizes suggest that these interactions remain agriculturally meaningful. This partial response may reflect temporal and biochemical mismatches between nitrogen supply and residue decomposition, which often govern nutrient availability in conservation-based systems. The lack of statistical significance of these interactions may be attributed to several factors. First, the relatively short experimental duration (two years) may not have provided sufficient time for soil-crop-nutrient interactions to fully develop and stabilize, as many soil biological processes require multiple growing seasons to reach equilibrium. Second, the high inherent variability in soil properties across the experimental plots, despite randomization, may have masked subtle interaction effects that could become apparent with larger sample sizes or longer observation periods. Third, the timing of residue incorporation and nitrogen application may have created temporal mismatches that prevented optimal synergistic effects, particularly given the differential decomposition rates of wheat residues under varying nitrogen availability. These explanations suggest that temporal scale and process synchronization are crucial determinants of integrative management success. It should be noted that the two-year duration of this study may not fully capture the long-term dynamics of these interactions because soil biological processes and nutrient cycling patterns often require multiple years to stabilize. Soil samples for analysis were randomly collected from six

different locations to minimize statistical error. Typically, soil fertility assessments in cultivated farmland are conducted at a depth of 0–30 cm, where more than 90% of the roots are located. While this approach is standard practice, focusing solely on the surface soil layer may have missed important deeper soil processes that could influence nutrient cycling and root-soil interactions, particularly in the subsoil zone where some crops extend their root systems. In some cases, it may be beneficial to collect samples from a second depth of 30–60 cm to provide a clearer picture of soil fertility under specific farm conditions (NENALAB, 12–13 October 2022). Thus, future long-term and multi-depth monitoring would improve the mechanistic understanding of residue–nitrogen–crop interactions.

Previous study has indicated that the immediate incorporation of residues with high carbon-to-nitrogen (C/N) ratios before planting can cause nitrogen immobilization, potentially reducing the yield of subsequent crops due to nitrogen deficiency. The net supply of nitrogen from crop residues depends on the residue type, environmental conditions, and the period from incorporation to sowing of the subsequent crop for decomposition processes (Singh and Sidhu 2014). This mechanism provides a plausible explanation for the observed neutral WRL $\times$ NL interaction, as nitrogen immobilization during early residue decay may have temporarily offset nitrogen mineralization benefits. The non-significant WRL $\times$ NL interaction in our study may also reflect the competing processes of nitrogen immobilization

and mineralization occurring simultaneously during residue decomposition, creating variable and offsetting effects that reduce the detectability of clear interaction patterns. Studies from different ecologies suggest that applying nitrogen fertilizer and organic amendments such as manure and crop residues (whether partially or fully retained after crop harvest) is crucial for restoring crop nutrients, thereby influencing attainable yields in cropping systems (Mucheru-Muna et al. 2007; Rusinamhodzi et al. 2011). Therefore, integrating organic and inorganic nutrient sources remains a promising approach for stabilizing soil fertility in diverse rotations, although local calibration of timing and dosage is essential.

Annual variations in biological yield were not significant; however, significant differences were observed in the grain and straw yields. This indicates that environmental fluctuations between years influenced the partitioning of assimilates rather than total biomass accumulation, likely through differential rainfall and temperature effects on grain filling. These results partially support our hypothesis regarding temporal variations, with year effects being more pronounced for economically important grain yields than for the total biomass production. The quality of straw produced in crop rotation systems involving maize and *Urochloa ruziziensis* can be enhanced by nitrogen fertilization applied to the preceding common bean crop, altering the content and accumulation of nutrients in the straw (Mingotte et al. 2020). The take-home message here is that inter-annual climatic variability interacts with management practices to affect yield components, emphasizing the need for adaptive management under changing climate scenarios.

Overall, these findings emphasize the importance of managing crop residues and nitrogen fertilization to optimize soil health and crop yield. The key insight of this study is that residue retention drives improvements in soil structure and nutrient status, while nitrogen fertilization fine-tunes nutrient availability and productivity; however, their interaction is context-dependent. Our results strongly support the overarching hypothesis that integrated residue and nitrogen management is essential for sustainable crop production, with differential responses between crop systems requiring tailored management strategies. The interaction between crop systems and residue management plays a crucial role in determining the soil properties and productivity. Additionally, while nitrogen fertilization is essential, its management needs to be balanced with residue incorporation practices to prevent potential issues, such as nitrogen immobilization, and to enhance the overall sustainability of agricultural systems. However, the regional specificity of our findings, conducted under particular soil and climatic conditions, may limit their direct extrapolation to other agro-ecological zones with different soil types or precipitation patterns. Sustainable residue management practices tailored to specific crop systems and

environmental conditions can improve the long-term soil fertility and support sustainable agricultural production. Hence, integrating residue management within site-specific nutrient strategies offers a viable path toward both agronomic and ecological resilience.

Although our results suggest the agronomic benefits of combined residue retention and nitrogen fertilization, it is important to acknowledge potential environmental trade-offs. Increased fertilizer inputs, while beneficial for yield, can accelerate nitrogen losses and greenhouse gas emissions if not properly managed. Although our study focused on productivity outcomes, we did not measure critical environmental parameters, such as nitrous oxide emissions or nitrate leaching, which are essential for comprehensive sustainability assessments, particularly given the potential for increased nitrogen losses under intensive fertilization regimes. Nitrogen fertilization, particularly at higher rates, can lead to increased nitrate leaching into groundwater and enhanced emissions of nitrous oxide (N_2O), a potent greenhouse gas (Butterbach-Bahl et al. 2013). In our study region, the risk of nitrate leaching is particularly relevant during the irrigation season. Thus, the environmental dimension of residue–nitrogen integration deserves equal attention in future work, linking agronomic benefits with ecosystem-level outcomes. Future research should incorporate measurements of N_2O emissions and nitrate leaching to develop truly sustainable management recommendations that balance productivity and environmental protection. The implementation of precision nitrogen management techniques and the use of enhanced-efficiency fertilizers could help mitigate these environmental concerns, while maintaining the yield benefits observed in this study.

Based on our findings, we recommend the following practices for the study region: (1) for wheat-maize systems: retaining all wheat residues (WR1) combined with 75–100% of conventional nitrogen rates to maximize yields while building soil organic matter; (2) for wheat-mungbean systems: full residue retention with 50–75% of conventional nitrogen rates provides optimal balance between productivity and input efficiency, as mungbean contributes to biological nitrogen fixation; (3) transition strategy: farmers currently removing residues should transition gradually, starting with 50% retention to allow soil biological communities to adapt; (4) economic considerations: while full residue retention showed the highest yields, the 50% retention level (WR2) provided 85–90% of the yield benefit, which may be more economically viable where residues have high market value for animal feed. These recommendations illustrate how integrative management can be fine-tuned to reconcile productivity, soil health, and resource-use efficiency. Future research should

extend these investigations across multiple years and locations, incorporate environmental monitoring, and include economic analyses to provide more comprehensive guidance for sustainable agricultural management decisions.

5 Conclusions

This study highlights the significant benefits of returning wheat residues to the soil and improving soil organic matter, aggregate stability, and nutrient availability. The integration of nitrogen fertilization with residue management further enhanced soil microbial activity and nutrient cycling. Although the interaction effects between nitrogen levels and residue management were not always significant, the overall impact on crop yields was positive. Maize and mungbean yields were significantly influenced by residue retention and nitrogen fertilization, with full residue retention (WR1) and optimal nitrogen levels leading to the highest yields. The study underscores the need for site-specific management strategies to balance residue retention and nitrogen fertilization for sustainable agricultural production. Sustainable crop residue management practices combined with the judicious use of nitrogen fertilizers are crucial for maintaining long-term soil fertility and achieving sustainable agricultural production. Further research is needed to explore these interactions across different agroecological contexts and over longer periods to fully realize the potential benefits of these practices.

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Declarations

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