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Sustainable intensification of potato zero-tillage using rice straw mulch: Optimizing agronomic practices in eastern India

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ABSTRACT

Potato production under zero-tillage with rice straw mulch (PZTM) is an innovative and sustainable approach that enhances crop productivity, profitability, and resource-use efficiency while mitigating greenhouse gas emissions. This study aimed to optimize mulching thickness, plant spacing, fertilization strategies, and potato varieties under PZTM conditions during the Rabi seasons of 2021–22 and 2022–23 in Patna, Bihar, India. A randomized complete block design was implemented, consisting of four trials and 12 treatments, replicated three times, to assess the effects of varying fertilizer sources, mulch thickness, plant spacing, and potato varieties. Results demonstrated that integrating organic and inorganic fertilizers yielded the highest agronomic and economic benefits, achieving a 60 % yield increase over the control. Environmental assessments revealed that treatments incorporating organic inputs significantly reduced C footprints compared to inorganic-only systems. Among the tested potato varieties, *Kufri Khyati*, *Kufri Uday*, *Kufri Jyoti*, *Kufri Thar-2*, and *Kufri Pukhraj* exhibited superior performance, yielding 35–38 t ha^{-1}, making them highly suitable for PZTM. Optimal mulch thickness (14–18 t ha^{-1}) and plant spacing (50 × 20 cm) enhanced yields and profitability while minimizing non-marketable tubers and greening. These findings underscore the potential of PZTM as a sustainable potato production system within rice-potato cropping systems. Adopting key PZTM agronomic practices—integrated fertilization, optimized mulching, and strategic spacing—can help farmers achieve higher yields, improved economic returns, and environmental sustainability. This study provides valuable insights for policymakers and farmers seeking to implement sustainable intensification strategies in potato cultivation.

1. Introduction

Contrary to the last decade's trends, India has surpassed China to become the most populous country in the world, with 1.441 billion inhabitants [1]. Agriculture remains the largest source of livelihood, with rice, wheat, and sugarcane as the main crops [2]. While small and marginal landholders contribute to high cultivation costs per hectare [3], Indian agriculture has achieved grain self-sufficiency. However, this achievement is resource-intensive, cereal-centric, and regionally biased, which raises serious concerns about its sustainability [2]. India's net cultivated area is approximately 141 Mha, nearly half of which lacks irrigation facilities [3]. Over 80 % of the country's freshwater is used for agricultural activities, making it the largest user of groundwater globally, accounting for approximately a quarter of the world's groundwater usage [4]. The growing pressure on water resources demands a re-evaluation of policies, particularly as desertification and land degradation significantly threaten Indian agriculture [2].

After China, India is the second-largest producer of potatoes, exporting them to countries such as Nepal, Oman, Sri Lanka, Malaysia, Indonesia, and Saudi Arabia [5]. India's northeastern and eastern regions, particularly Bihar, are known for their potato production [5]. However, India's per-hectare potato productivity is 20.6 t ha^{-1}, nearly

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half of the productivity in Northwestern European countries, reaching 42.2 t ha^{-1} in 2021 [6]. To meet the increasing demand for food and feed, there is a pressing need to sustainably intensify production in smallholder systems. If appropriate measures are not taken, traditional agricultural practices—such as repeated tilling, burning crop residues, overusing water, and applying fertilizers indiscriminately, along with the reliance on outdated machinery—will lead to increased water depletion [7], soil degradation [8], and a higher C footprint in agriculture in the future [9]. Furthermore, ensuring the sustainable use of natural resources will pose a significant challenge in developing an efficient and profitable agricultural system [10]. Potential solutions include conservation practices such as zero tillage, organic mulching, and precision water and residue management, which conserve water and enhance economic benefits [11]. For instance, crop residue recycling, particularly paddy straw mulch, in subsequent Rabi crops had several positive impacts on the soil and crop yield and quality [12].

Estimating the overall C footprint of production technologies is crucial for identifying resource-efficient and resilient practices [13]. Nitrogen use efficiency is also crucial since N is essential for crop development. It is an important index that can be used in conservation agriculture to quantify different nutrient management practices and determine treatment effectiveness [14]. Studies have shown a direct link between N availability, canopy size, and radiation use efficiency [15]. However, excessive applications during fertilization could lead to nitrate contamination of surface and groundwater systems [16]. In the long run, the amount of N applied contributes to its accumulation in the soil, leading to acidification [17] and affecting N_2O emissions in the future [18]. In the specific case of potatoes, the crop is considered to have poor N uptake efficiency due to a poorly developed root system. However, reliable comparisons with other crops are limited. Combined with the N inputs often used, this raises concerns about N losses that are both unproductive and environmentally undesired [16]. While poor N recovery is observed in potatoes, it should not be presumed to be the norm for the species, since it has a greater genetic diversity that can contribute to adaptation to a wide range of climates and conditions [19].

Previous experiences from non-controlled trials in different regions have demonstrated that potatoes can be effectively cultivated using zero-tillage covered with rice mulch (PZTM) [12,20,21]. To our knowledge, there is no systematic research evidence on the impact of PZTM's best agronomic management practices on productivity, profitability, resource use efficiency, and C footprint. Studies suggest that PZTM is a promising technology for smallholder farmers that can significantly contribute to the agroecological transformation of many Asian countries [22]. This study evaluated different management aspects that can influence the performance of PZTM in four simultaneous field trials, with the objectives to provide evidence on a systematic basis under controlled conditions for: i) the optimal source, combination and amount of fertilizer for increased nutrient use efficiency with a low carbon footprint, and ii) how varietal differences, rice mulch thickness, and plant spacing influence the agronomic and economic performance of potato crops under PZTM. We hypothesize that optimal agronomic management practices for PZTM can be recommended to farmers, enhancing cropping system intensification, resource use efficiency and increasing productivity and profitability in South Asia.

2. Materials and methods

2.1. Experimental site

The four PZTM trials were conducted at the Indian Council of Agricultural Research-Central Potato Research Institute, Patna (25°35′32″ N, 85°4 ′29″ E, 53 m asl), Bihar, India, during the Rabi season (winter cropping season, November–March) of 2021–22 (season 1) and 2022–23 (season 2). The site has a monsoon-influenced humid subtropical climate (Cwa code in the Köppen climate classification), characterized by an average yearly rainfall of 984.7 mm, 87 % of which occurs in June–September and mean monthly minimum and maximum temperatures of 9.1 °C in January and 38.0 °C in May, respectively (1951–2000 period; [23]). During both seasons, minimum and maximum temperatures ranged from 5.5 to 19.0 °C and 12.8–34.1 °C, respectively, while precipitation reached 74.0 mm in season 1 and only 0.2 mm in season 2 (Fig. S1). The soil was sandy loam in texture, with a pH of 7.4 (soil:water ratio 1:2), a low Walkley-Black carbon content (0.32 %), an available N (permanganate oxidizable) of 143.2 kg ha^{-1}, a 0.5 M $NaHCO_3$-extractable P content of 16.7 kg ha^{-1} [24], and an exchangeable K content of 137.2 kg ha^{-1}. Rice is the primary crop in this area during the wet season (June–November, Kharif season), which is typically grown as a rainfed crop. In contrast, wheat and potato crops are cultivated during the subsequent season, known as the Rabi season.

2.2. Experimental details and treatments description

This study tested four agronomic management factors—fertilization, variety, mulching, and plant spacing—across four PZTM simultaneous trials, each arranged in a randomized complete block design with twelve treatments (12 variations of a specific factor) replicated three times in both seasons. The experiment covered a total area of 1152 m^2; each trial occupied 1/4 of it. Replications consisted of plots of 2 m × 4 m, and each plot occupied an area of 38 m^2. In each trial, one factor varied across 12 treatments while the other three remained constant (Fig. 1). In the first trial (Trial 1), the variable factor was the fertilization source and rate. Treatments (F1–F11) consisted of different percentages (50–125 %) of the recommended dose of fertilizer (RDF; 150-80-100 kg ha^{-1} of N-P-K), some combined with varying rates of organic fertilizers—farmyard manure (FYM) and/or vermicompost (VC)—, as well as a "control" treatment (F0) with no fertilization (see details in Table S1). In the second trial (Trial 2), the variable factor was the variety of potato used. Treatments (V1–V12) included only early- and moderate-maturity varieties, most of which were moderately resistant to late blight (*Kufri Pukhraj*, *Kufri Arun*, *Kufri Lalima*, among others), but also included some susceptible and resistant varieties (see details in Table S2). In the third trial (Trial 3), the variable factor was the mulch material and thickness level. Treatments (M1–M12) consisted of varying thickness (from 6 to 20 t ha^{-1} with 2 t ha^{-1} increments) of primarily rice straw mulch, but also included other organic mulches (jute matting, neem leaf litter, and Doob grass weed) and a treatment with plastic mulch (see details in Table S3). In the fourth trial (Trial 4), plant spacing was the variable factor. Treatments (S1–S12) consisted of various combinations of row spacing (30–60 cm) and plant spacing (20–40 cm), resulting in plant densities ranging from 6.25 to 16.7 individuals m^{-2}. Different planting arrangements were also tested, including staggered row planting and soil-covered shallow planting (see details in Table S4). The experimental site had been under a potato-fallow-dhaincha (for green manuring) cropping system for over five years before the initiation of the experiment in 2021.

2.3. Crop management and irrigation

In both seasons, a common management approach was maintained for the four tested factors (fertilization, variety, mulching, and plant spacing) across all trials, following the procedure for PZTM trials outlined by Kakraliya et al. [10]. However, when a factor was tested as a treatment (see Section 2.2), the common across-trials management was included as one of its 12 treatments. Thus, the common across-trials fertilizer dose was an RDF of 150-80-100 kg ha^{-1} of N-P_2O_5-K_2O, applied 5 cm away from the tubers at planting. In Trial 1, inorganic (diammonium phosphate, potassium chloride, and urea), organic (FYM and vermicompost), and a combination of organic + inorganic fertilizers were used as per the treatment protocol (F1 to F11 in Table S1). Additionally, in trials 2, 3 and 4, a foliar spray of 19-19-19 kg (N-P-K) at 10 g L^{-1} of water was applied at 30 days after planting (DAP), followed by a second spray of 13-0-45 kg (N-P-K) at 10 g L^{-1} of water at 45 DAP. The

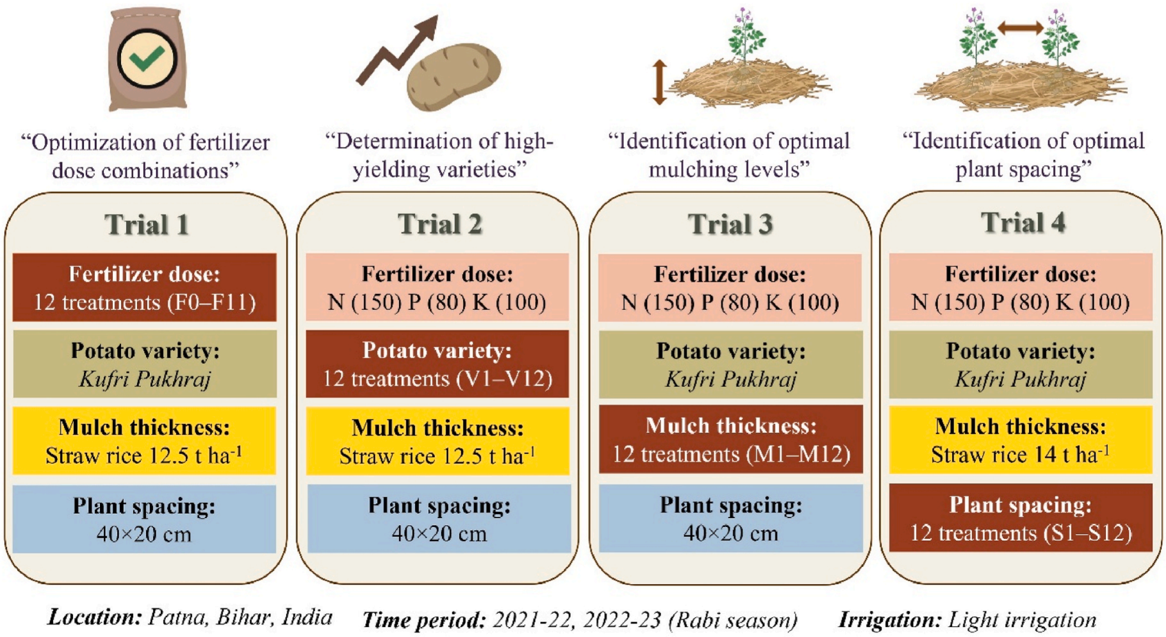

Fig. 1. Overview of the trials on potato zero-tillage with rice straw mulching conducted in this study. Four simultaneous trials (columns) testing four agronomic management factors (rows), with each trial varying one factor (reddish-brown box) across 12 treatments while keeping the other three constant. This image was created using BioRender.com. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

standard variety across trials was *Kufri Pukhraj*, an early-maturing cultivar widely grown in the North Indian plains and Plateau regions, known for its drought tolerance and moderate resistance to late blight [25]. The common across-trials mulching thickness was 12.5 t ha^{-1} of rice straw, applied at planting, ensuring full soil coverage to prevent solanine formation and tuber greening [10]. The standard plant spacing across trials was 40 cm between rows and 20 cm within rows, resulting in a plant density of 12.5 plants m^{-2}. Tubers weighing 25–30 g with at least two sprouting eyes were planted by using residual soil moisture of rice field (rotten or shriveled tubers were excluded), totaling approximately 3.5 t ha^{-1} of seed tubers. In all trials, planting occurred on 10 December in Season 1 and 4 December in Season 2, while the harvest occurred between 10 and 15 March during both seasons.

After rice was harvested, residual soil moisture was used to plant the potato crop. The first irrigation was applied at 10–12 DAP, and subsequent irrigations were scheduled based on available soil moisture in different trials and their respective treatments. Flood irrigation was applied in all the treatments. The amount of irrigation water applied to each plot was measured using a bucket. The total amount of water applied (input water) was computed by summing the irrigation water and rainfall (Table S1–S4).

2.4. Yield, economic analysis, and agronomic efficiency of nutrients

At harvest time, the total tuber weight per plot (in kg) was recorded and then classified into marketable (weight >25 g) and non-marketable tubers (weight <25 g). Subsequently, total yield (TY), marketable yield (MY), and non-marketable yield (NMY) in tons per hectare were computed as the ratio of tuber weight per plot-to-plot area, multiplied by 10. For Trial 3, the percentage of green tubers (PGT) was calculated as the ratio of green tuber yield—defined as the yield of tubers with more than 25 % of their surface visibly green due to light exposure—to the total tuber yield, following the methodology described by Zarina et al. [26]. An economic analysis was conducted using prevailing market prices of inputs, labor, and produce in Indian rupees (INR, Rs) for 2021–2023, then converted to US dollars (USD) for comparison. Economic indicators were estimated using both fixed and variable costs, following the methodology of Sarangi et al. [20]. The fixed cost included land rent, depreciation of machinery, and interest on working capital. Variable costs included human labor, tractor operational expenses, and the cost of production inputs such as seeds, compost, fertilizer, pesticides, irrigation, and harvesting, among other expenses. The cost of human labor used was based on labor days per hectare, assuming an 8-h working day, as per Indian labor law. All these fixed and variable costs were summed up to calculate the total cost of production. Gross returns were calculated based on the prevailing market prices of the potato tuber over the different years. The benefit-cost ratio (BCR) was calculated as the ratio of gross returns to total cost of production [20].

Only in Trial 1, the agronomic efficiency of total nutrients (AE) and of N (AE_N) was used as an integrative indicator of resource use efficiency. For each fertilizer treatment, AE (Eq. (1)) was calculated by comparing its TY with that of the "control" (kg ha^{-1}), divided by the total amount of nutrient (N + P + K) applied (kg ha^{-1}). Similarly, AE_N (Eq. (2)) was calculated using the same TY difference, but divided by the total amount of N applied (kg ha^{-1}). Both indicators more closely reflect the direct production impact of an applied fertilizer and are directly related to economic return [27].

$$AE = \frac{TY_{fertilizer\ treatment} - TY_{control}}{Total\ nutrient\ applied} \tag{1}$$

$$AE_N = \frac{TY_{fertilizer\ treatment} - TY_{control}}{Total\ N\ applied} \tag{2}$$

2.5. Estimation of greenhouse gas emissions and global warming potential

The Climate Change, Agriculture and Food Security (CCAFS) Mitigation Options Tool (CCAFS-MOT; Feliciano et al. [28]) was used to estimate greenhouse gas (GHG) emissions from the production systems in Trial 1. This tool employs a combination of several empirical models to calculate GHG emissions within a production system, considering various factors that include climatic conditions, soil characteristics, crop production inputs, and other relevant management practices [28]. The net C footprint (CF) of different cropping systems was estimated considering all the sources and sinks of GHGs. These include CO_2 emissions from fertilizer production, urea application, and fuel combustion; N_2O emissions from direct soil processes and indirect pathways such as NH_3 volatilization, NO_x release, and N leaching; and CH_4 emissions from manure management. All GHGs are converted into CO_2-equivalents (CO_2-eq.) using the global warming potential (over 100 years) of 34 and 298 for CH_4 and N_2O, respectively [29]. Finally, total CF was calculated on a per-unit basis of tuber yield as follows:

$$CF\left(kgCO_2eq.t^{-1}\right)=\frac{CO_2\left(kgha^{-1}\right)+298*N_2O\left(kgha^{-1}\right)+34*CH_4\left(kgha^{-1}\right)}{TY\left(tha^{-1}\right)} \quad (3)$$

2.6. Statistical analysis

An analysis of variance (ANOVA) was performed to evaluate the effect of the treatments (and its interactions with seasons) involving fertilizer doses (Trial 1), potato varieties (Trial 2), mulch thickness levels (Trial 3), and plant spacing (Trial 4) on the agronomic (TY, MY, and NMY) and economic (BCR) variables using R [30]. Additionally, in Trial 1, ANOVA was also applied to the environmental (CF) and agronomic efficiency (AE and AE_N) indicators. Subsequently, significant differences (p-value <0.05) among treatments were detected for all these variables/indicators using the least significant difference test of the "Agricolae" package [31]. Furthermore, Pearson correlation analysis was performed for the agronomic indicators.

Table 1
ANOVA F-values for agronomic (TY = total tuber yield, MY = marketable yield, and NMY = no marketable yield) and economic (BCR = benefit-cost ratio) indicators from four (Trials 1–4) potato zero-tillage trials in Patna, India. Trial 1 included nutrient efficiency (AE = agronomic efficiency of total nutrient; and AE_N = agronomic efficiency of N) and environmental (CF = carbon footprints) indicators. *, **, and *** indicates significant effect at p-value of <0.05, <0.01, and <0.001, respectively. TT = treatment.

Variable/ Source	2021–2022	2022–2023	Both seasons		
	TT	TT	TT	season	TT × season
Trial 1: Fertilizer trial					
TY	21.5***	30.6***	51.5***	3.79	0.50
MY	41.3***	63.9***	103.4***	2.40	0.64
NMY	40.1***	45.7***	84.4***	5.0*	1.24
BCR	17.0***	24.7***	41.5***	47.7***	0.61
AE	4.7**	3.3*	2.6*	7.7**	0.06
AE_N	7.4***	10.1***	6.2***	7.1*	0.06
CF	114.0***	160.6***	256.8***	5.2*	0.81
Trial 2: Varietal trial					
TY	14.4***	5.4***	12.0***	5.6*	7.4***
MY	20.4***	10.8***	23.1***	8.3**	6.4***
NMY	11.2***	8.4***	15.2***	0.00	4.6***
BCR	8.7***	4.9***	10.1***	0.01	3.7***
Trial 3: Mulching trial					
TY	17.1***	25.6***	36.1***	15.8***	0.33
MY	102.2***	80.5***	168.7***	22.9***	0.55
NMY	93.2***	177.5***	212.3***	0.17	2.1*
BCR	63.1***	52.7***	104.7***	40.9***	0.62
Trial 4: Plant Spacing trial					
TY	13.3***	7.9***	20.9***	5.4*	0.44
MY	10.0***	6.5***	16.2***	3.66	0.48
NMY	49.7***	15.7***	52.0***	16.4***	3.5**
BCR	3.5**	4.2**	7.2***	2.70	0.52

3. Results

3.1. Performance of potato crop under 11 different fertilizer dose combinations, zero tillage, and rice straw mulch practices

In Trial 1, TY, MY, NMY, and BCR showed significant treatment effects, with NMY and BCR also differing significantly between seasons (Table 1). TY ranged between 20.4 and 36.4 t ha^{-1} and 19.4–37.9 t ha^{-1} in seasons 1 and 2, respectively (Fig. 2A and B). F9 showed significantly higher TY than F5, F6, F11, and F0 in both seasons, and more than F3 and F4 in season 2 (Fig. 2A and B). F0 showed the lowest TY in both seasons, followed by F11. High-yielding TY treatments presented a pattern of decrease in NMY (r = −0.64; Fig. 2A and B), while TY was strongly and positively correlated with MY (r = 0.98). BCR ranged between 0.93–1.49 and 0.95–1.63 in seasons 1 and 2 (Fig. 2C and D), respectively, and mirrored the TY trend. F9 consistently had the highest BCR, differing significantly from F6, F11, and F0 in both seasons and from F5 and F3 in season 2 (Fig. 2C and D). Overall, total cost of production (range: 2019.2–2267.2 USD ha^{-1}) was primarily contributed by seeds (57–64 %) and labor (19–22 %), followed by mulching (~13 %), and fertilizer + compost, which accounted for 2.8 % in F11 to 7.2 % in F6 (Fig. S2A).

Significant effects among treatments and between seasons were observed for AE, AE_N, and CF (Table 1). AE_N ranged from 67.2 to 145.8 kg kg^{-1} in season 1 and from 82.3 to 160.0 kg kg^{-1} in season 2, with F5 showing the highest values in both seasons and significantly surpassing all treatments except F4 in season 1 (Fig. 3A and B). In general, AE (ranging between 25.8–44.7 and 34.3–50.9 kg^{-1} for seasons 1 and 2, respectively) did not show significant variations among treatments (Fig. 3A and B). CF ranged between 19.7–95.2 and 20.7–88.2 kg CO_2-eq. t^{-1} corresponding to seasons 1 and 2, respectively (Fig. 3B and C). In both seasons, F6—followed by F2 and F8—showed the highest CF values, primarily driven by the manure source in F6 and F8, while F0 recorded the lowest CF (Fig. 3C and D). The fertilizer source was the primary driver of CF for all other treatments, except for F6, F8, and F0 (Fig. 3C and D).

3.2. Performance of different potato varieties under zero tillage and rice straw mulch practices

In Trial 2, TY, MY, NMY, and BCR showed significant effects among treatments, with TY and MY also varying between seasons, and all variables showing significant treatment × season interactions (Table 1). TY ranged between 25.0 and 38.0 t ha^{-1} in season 1 and 31.0–38.4 t ha^{-1} in season 2 (Fig. 4A and B). V11 consistently showed the highest TY, differing significantly from V2, V4, and V6 in both seasons, as well as from V1 and V10 in season 1, and from V8 in season 2 (Fig. 4A and B). MY was highly correlated with TY (r = 0.94), conversely to NMY, which had no relation (r = 0.19). BCR ranged between 1.35–1.70 and 1.35–1.63 in season 1 and 2, respectively (Fig. 4C and D). In season 1, V7 showed the highest BCR, followed by V11, V5, and V12, with no significant differences among them (Fig. 4C). In season 2, V11 showed the highest BCR, differing significantly only from V8, V2, V6, and V4 (Fig. 4D). Overall, total cost of production (range: 2196.4–2338.8 USD ha^{-1}) was similar across treatments, with seeds (57.3–61.5 %) and labor (19.9–22.8 %) being the main contributors (Fig. S2B).

3.3. Performance of potato crop under 12 different mulching practices

In Trial 3, TY, MY, and BCR varied significantly among treatments and between seasons, while NMY showed significant effects only among treatments and in the treatment × season interaction (Table 1). TY ranged between 24.8 and 39.3 t ha^{-1} in season 1 and 26.3–41.8 t ha^{-1} in season 2 (Fig. 5A and B). M11 had the highest TY, differing significantly from M9, M10, M3, M2, and M1 in both seasons, and additionally from M12 in season 2 (Fig. 5A and B). Across both seasons, treatments that

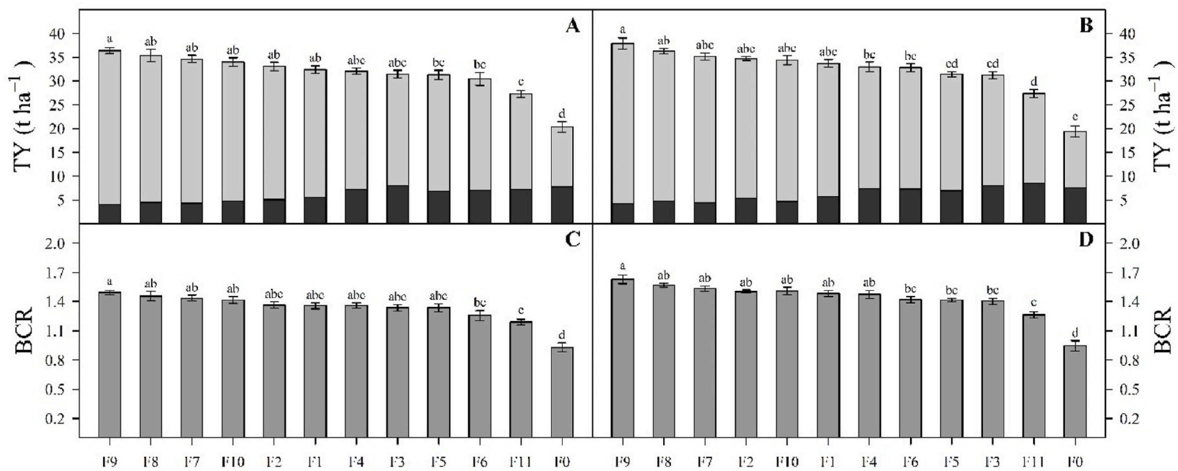

Fig. 2. Agronomic (A and B) and economic (C and D) indicators of potatoes (*Kufri Pukhraj* variety) cultivated with eleven fertilizer dose treatments (F1–F11; see definitions in Table S1), and without fertilizer application (F0; control), under zero-tillage with rice straw mulch practices across the 2021-22 (A and C) and 2022-23 (B and D) Rabi seasons in Patna, Bihar, India. TY: total tuber yield = marketable (light gray bars) + nonmarketable (black bars) tuber yield. BCR: benefit-cost ratio. Different letters on top of the bars represent significant differences among treatments within each sub-figure.

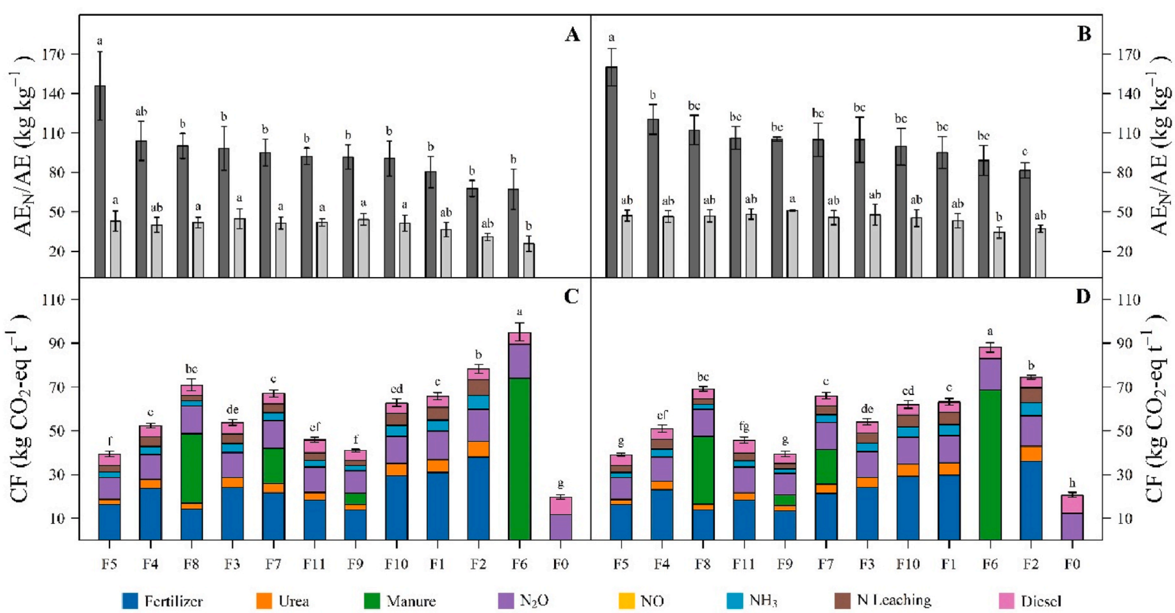

Fig. 3. Agronomic efficiency of N (AE_N, dark gray bars; A and B), agronomic efficiency of total nutrients (AE, light gray bars; A and B), and carbon footprint (CF; C and D) of potatoes cultivated with eleven fertilizer dose treatments (F1–F11, see definitions in Table S1) under zero-tillage with rice straw mulch practices across the 2021–22 (A and C) and 2022–23 (B and D) Rabi seasons in Patna, India. Different letters on top of the bars represent significant differences among treatments within each variable and sub-figure.

used rice-straw as mulch (M5–M8) consistently ranked among the highest yielding treatments (Fig. 5A and B). A decreasing pattern in NMY was observed among the high-yielding TY treatments (r = −0.80, Fig. 5A and B). In both seasons, PGT was highest (26–71 %) in M1, M2, M3; intermediate (8–13 %) in M4, M9, M10, and M12; and lowest (2–6 %) in M5, M6, M7, M8, and M11 (Fig. S3). BCR ranged between 0.75 and 1.90 in season 1, and 0.92–2.07 in season 2, following a similar trend to TY (Fig. 5C and D). M11 showed the highest BCR in both seasons, significantly surpassing all treatments except M5 in season 1 (Fig. 5C and D). M1 was not profitable (BCR <1) in both seasons, and M2 was also unprofitable in season 1 (Fig. 5C and D). Overall, total production cost (range: 2039.3–2633.4 USD ha^{-1}) in this trial was higher than in the other trials, except for treatment S1 in Trial 4 (Fig. S2). Main contributors were seed cost (49.8–63.3 %), followed by labor (19.0–26.6 %), and mulch cost, the latter accounting from 2.6 % (M11) to 23.5 % (M10) (Fig. S2C).

3.4. *Performance of potato crop under different plant-spacings and geometry under zero tillage with rice straw mulching*

In Trial 4, TY, MY, NMY, and BCR showed significant treatment effects, with TY varying between seasons, and NMY being influenced by both seasons and treatment × season interactions (Table 1). TY ranged between 25.7 and 40.0 t ha^{-1} in season 1, and 29.1–41.3 t ha^{-1} in season 2 (Fig. 6A and B). S1 recorded the highest TY (followed by S11 and S3, with no differences among them), differing significantly from S5, S7, S9, and S10 in both seasons, as well as from S6 in season 1 (Fig. 6A and B). Both MY (r = 0.98) and NMY (r = 0.91) were positively correlated with

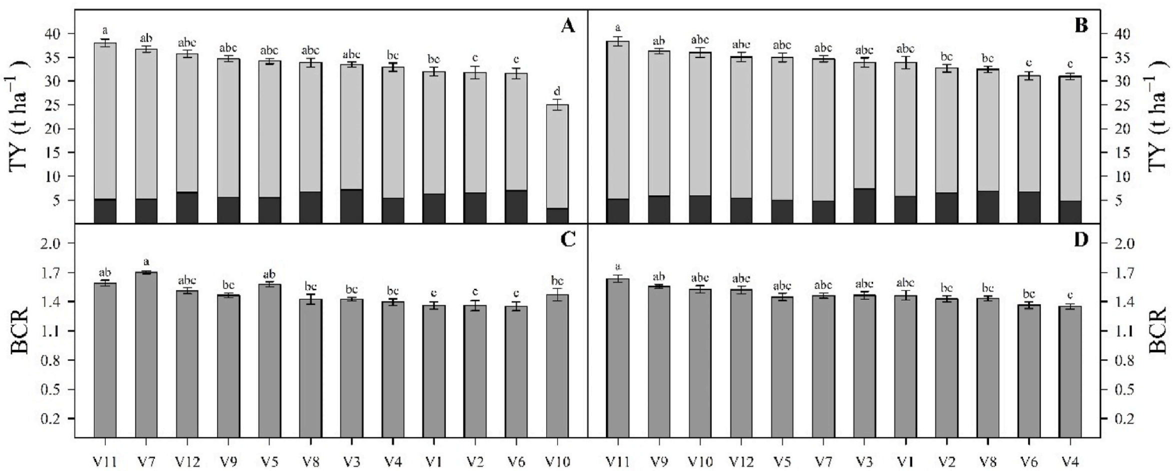

Fig. 4. Agronomic (A and B) and economic (C and D) indicators of twelve potato varieties (V1–V12, see definition in Table S2) cultivated under zero-tillage with rice straw mulch practices across the 2021–22 (A and C) and 2022–23 (B and D) Rabi seasons in Patna, India. TY: total tuber yield = marketable (light gray bars) + non-marketable (black bars). BCR: benefit-cost ratio. Different letters on top of the bars represent significant differences among treatments within each sub-figure.

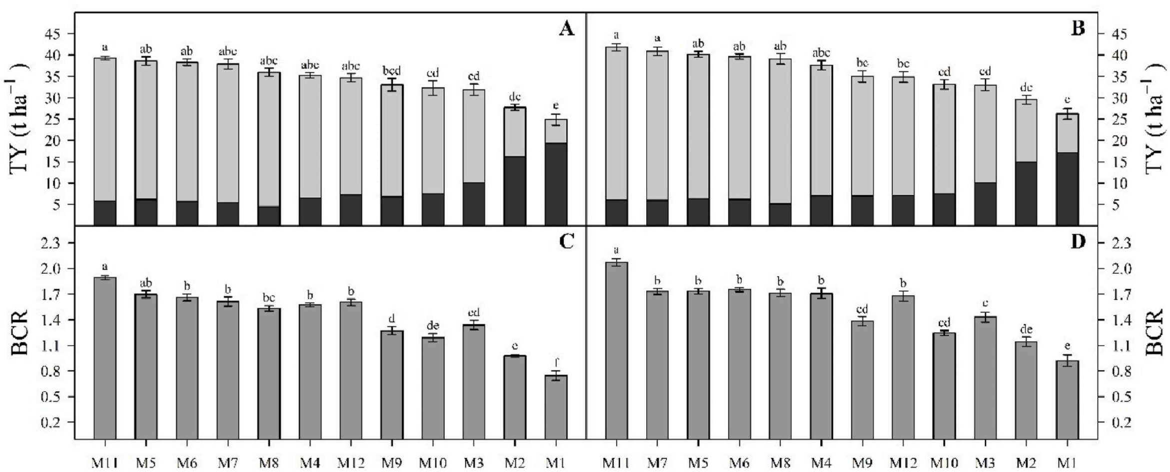

Fig. 5. Agronomic (A and B) and economic (C and D) indicators of potatoes cultivated with different mulch rice thickness (M1-M8) and other materials (M9-M12, see definitions in Table S3) and zero-tillage across the 2021-22 (A and C) and 2022-23 (B and D) Rabi seasons in Patna, India. TY: total tuber yield = marketable (light gray bars) + non-marketable (black bars). BCR: benefit-cost ratio. Different letters on top of the bars represent significant differences among treatments within each sub-figure.

TY in both seasons. BCR ranged between 1.37–1.91 and 1.40–1.94 in seasons 1 and 2, respectively (Fig. 6C and D). In season 1, S8 had the highest BCR, significantly differing only from S1, which had the lowest BCR in both seasons (Fig. 6C). In season 2, S7 had the highest BCR, with significant differences only with S1 (Fig. 6D). Overall, the total cost of production in this trial was the most variable among trials, ranging from 1565.9 USD ha^{-1} in S7 to 2929.2 USD ha^{-1} in S1, with seeds (42.6–60.7 %) and labor (22.3–25.5 %) being the main contributors (Fig. S2D).

4. Discussions

4.1. Combined organic-inorganic fertilizers boost potato yields by 50 % with a lower C footprint

The average potato yield in Bihar is approximately 18 t ha^{-1}, below the national productivity average of around 21 t ha^{-1} [32]. Mandal et al. [32] reported that the *Kufri Ashoka* variety produced yields close to 24 t ha^{-1} under different customized fertilizer regimes. In this study, the *Kufri Pukhraj* variety under different fertilizer doses (F1 to F11) yielded notably superior to the published data, at least 50 % higher. This might be due to improved management practices like zero-tillage, crop residue mulching, proper crop establishment [33], good quality seeds, precise water [34], and higher nutrient availability [35]. In contrast, the control (no fertilizer applied) yields were approximately 20 t ha^{-1}, consistent with the literature. Considering that these results were obtained under controlled conditions, it is plausible to assume that most Indian potato farming practices lack the adoption of good agricultural practices and adequate fertilization [36]. Additionally, using poor-quality seed and inadequate pest and disease control is another major contributor to poor average farm yields besides suboptimal fertilization [36]. Combining fertilizers with conservation agriculture practices, such as PZTM, could significantly enhance crop performance [11,14]. The RDF used in this study (NPK 150:80:100 kg ha^{-1}) was based on the economic optimum nutrient levels for Bihar, as determined by the State Agriculture University and the Indian Council of Agricultural Research. According to Mandal et al. [32], this customized fertilizer recommendation is aligned with current farming practices and is likely to be well received by local farmers.

Among the fertilizer combinations tested, F9 (50 % RDF + 7.5 t ha^{-1} FYM + 2.5 t ha^{-1} VC) demonstrated the best performance in terms of

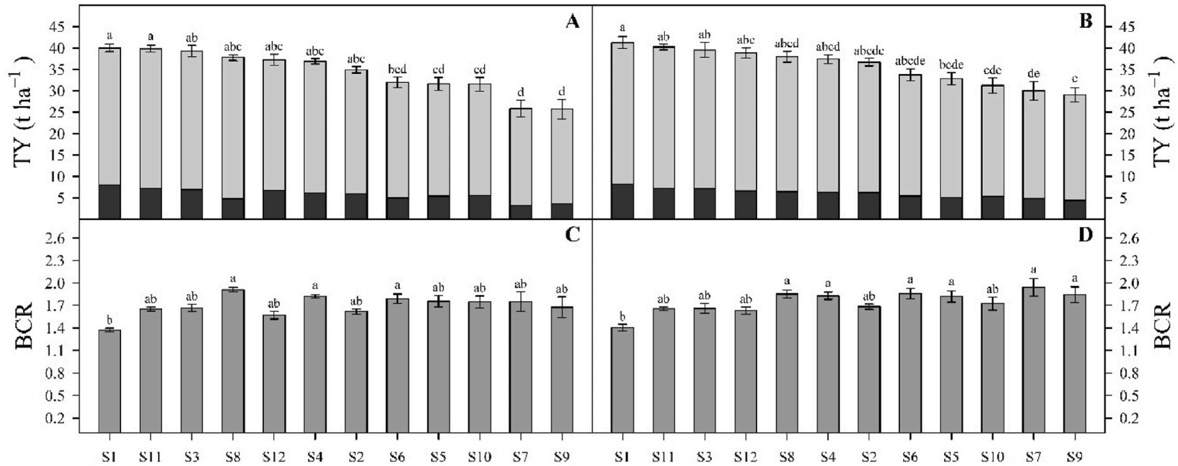

Fig. 6. Agronomic (A and B) and economic (C and D) indicators of potatoes cultivated with different plant-spacings (S1–S12, see definitions in Table S4) under zero-tillage with rice straw mulching across the 2021–22 (A and C) and 2022–23 (B and D) Rabi seasons in Patna, India. TY: total tuber yield = marketable (light gray bars) + non-marketable (black bars). BCR: benefit-cost ratio. Different letters on top of the bars represent significant differences among treatments within each sub-figure.

agronomic, economic, and resource use efficiency indicators, which positively influenced crop growth and tuber yield [37]. Additionally, the proper decomposition of FYM and VC provides readily available plant nutrients to the crops and improves the soil environment. This enhancement increases the nutrients and water-holding capacity of the soil over a longer period, resulting in better agronomic, economic, and resource use efficiency than other treatments [27,37]. The treatments that combined organic and inorganic fertilizers (such as F9) were the most expensive but also yielded the highest BCR. These findings align with previous research that has reported increased productivity and economic profitability from combining organic and inorganic fertilizers [27,38].

The overall results of the tested inorganic fertilizers revealed that in the PZTM system, NPK and N fertilizers could be reduced by 25 % without negatively affecting yields and BCR, compared to applying the full RDF. This reduction can be attributed to improved establishment, rooting, and enhanced availability of moisture and nutrients under the PZTM system [35]. These findings indicate that PZTM is effective even with a 25 % reduction in N input, aligning with Ramírez et al. [22], who pointed out that previous studies have shown PZTM to enhance AE and AE_N. Furthermore, the side placement of fertilizers (F10) led to numerically better yields and higher fertilizer use efficiency than the method of surface applications of RDF (F11; Fig. 2A and B). This improvement is likely due to increased nutrient availability and reduced losses compared to the surface application method [39]. In line with these findings, Mandal and Sharma [40] discovered that most variation in potato tuber yields in conditions like this study was primarily due to the N application. Even though no N was applied in the "control" treatment, the yields were close to the national average reported by Mandal et al. [32]. This may be attributed to residual soil nutrients from the previous rice crop, improved soil moisture, and enhanced N availability under conservation agriculture practices [16,33,41]. Moreover, conservation agriculture-based management practices are recognized for promoting larger, deeper root systems and achieving higher N use efficiency [42].

According to data from the Government of India [43], CF from agriculture in 2019 was primarily attributed to enteric fermentation (1583.3 kg CO_2-eq. ha^{-1}), agricultural soils (627 kg CO_2-eq. ha^{-1}), and rice cultivation (520.8 kg CO_2-eq. ha^{-1}). The contribution from residue burning was relatively low, at 59.3 kg CO_2-eq. ha^{-1}. In this trial, the CF ranged from 20 to 95 kg CO_2-eq. t^{-1} for both seasons, which is lower than findings from recent reports indicating that potatoes grown under optimal conditions had a CF between 41 and 330 kg CO_2-eq. t^{-1} [38]. Notably, the "controls" not using fertilizers had a CF close to 20 kg CO_2-eq. t^{-1}. Research has shown that yield and the amount of N fertilizer applied are the most significant factors influencing GHG emissions. Therefore, maximizing yield can help reduce CF when the cumulative emissions of a cultivated area are divided by its yield [18]. Kakraliya et al. [13] found a strong positive correlation between CF (measured in Global Warming Potential) and yield. The high yields obtained in this study may have significantly affected the CF, with fertilizers being the largest source of CO_2 emissions, as noted by Rinza et al. [44]. However, the significance of N fertilizer can be overestimated when considering N_2O emissions from soil and the production of mineral fertilizers, as this GHG gas can arise from various other factors [45]. Despite this, prioritizing yield maximization could negatively impact other environmental aspects. Notably, crop protection chemicals have little effect on the CF, and reducing or excluding pesticides would likely lead to a substantial decrease in yield, negatively impacting the CF of potato crops, which are often treated with fungicides [18]. Conversely, scenarios involving retaining residues, such as mulching, tend to emit less CH_4 than incorporating residues into the soil. This is likely because mulching creates a less anaerobic environment by reducing irrigation requirements [13]. Previous studies have advocated integrating organic and inorganic nutrients for sustainable crop production in India [46,47]. While these methods may require a higher initial investment, the resulting benefits in production, nutrient efficiency, and reduced emissions under controlled conditions justify the investment.

4.2. PZTM and optimized varieties significantly improve potato agronomic and economic performance

In contrast to Trial 1, Trial 2 displayed significant differences concerning agronomic and economic indicators between treatments and seasons. These differences were primarily due to the replacement of certain varieties (V3, V6, V8, V10) between the two seasons. TY of the potato varieties tested in this trial were consistent with previously published potential yields of these varieties [48]. This improved performance may be attributed to the enhanced effectiveness of potato varieties resulting from the new crop establishment method. Over two years, the top-performing varieties under PZTM were *K. Khyati, K. Uday* (UNICA), *K. Jyoti, K. Thar-2,* and *K. Pukhraj*. *K. Pukhraj*—the same variety used in the other trials— yielded nearly as much as one of the highest results achieved with a fertilization dose combining organic and inorganic inputs in Trial 1. Similarly, *K. Ashoka* (V6 in season 1), a widely grown potato variety in India [32], yielded an average of 31.6 t ha^{-1}, outperforming other studies. Besides local varieties, there were improved Peruvian potato varieties like UNICA (*K. Uday,* V7 in both seasons) and Canchán (*K. Kanchan*, V6 in season 2), both of which have potential yields of up to 40–50 t ha^{-1} [49]. Local studies consider *K. Uday* an early maturing variety capable of producing 36–38 t ha^{-1} when following the standard agronomical schedule of potato [50]. However, when tested and compared with other local varieties like *K. Lalima* (V4), *K. Uday* yielded 43.0 t ha^{-1}, while *K. Lalima* yielded 35.7 t ha^{-1}. Management practices were consistent across all varieties (treatments), resulting in nearly identical production costs. However, there were significant differences in BCR, indicating that the different varieties, with their varying agronomic potentials, significantly influence economic profitability. Unlike Trial 1, where the same quantity of irrigation water (180 mm ha^{-1}) was applied to all the treatments, this trial provided different amounts of water to each treatment (Table S2). For instance, *K. Surya* (V1), *K. Lalima* (V4), *K. Jyoti* (V9), and *K. Khyati* (V11) received 25 % more water (240 mm ha^{-1}) compared to the other treatments. The higher water demand may be attributed to longer durations and increased evapotranspiration rates through the potato canopy, which could affect yield; however, only V11 exhibited a significantly higher yield than the others. This indicates that irrigation was not the primary factor driving yield differences. Instead, as noted by Kim and Lee [51], high day/night temperatures can cause tuber yield losses of 17.2–30.3 %, suggesting that thermal stress may have played a more critical role. Moreover, varietal differences likely influenced these responses; for instance, V11 is resistant to late blight, whereas the other varieties ranged from susceptible to moderately resistant (Table S2).

4.3. Mulch type and thickness are critical for maximizing potato yield and minimizing green tuber defects

The optimum thickness of rice straw to produce maximum yield and BCR while reducing green tuber quantity ranged between 14 and 16 t ha^{-1} (M5–M6). These improvements are likely due to improved soil moisture and nutrient availability, and decreased soil temperature resulted in better crop growth and yield, while providing sufficient protection from sunlight to avoid greening [10]. Based on the results of Trial 3, applying 14–16 t ha^{-1} of residue can be recommended, as it may reduce the incidence of green tubers and proportionally improve marketable yield compared with the 12.5 t ha^{-1} used in the other trials. Recent studies have demonstrated that using paddy straw mulch to cover the soil surface effectively reduces weed populations [9]. Covering the soil surface with an appropriate amount of paddy straw mulch is a barrier to heat penetration and helps to reduce evaporation of soil moisture, allowing the retained soil moisture to be utilized effectively for crop development [52]. An optimum thickness of paddy straw prevents the formation of chlorophyll and glycoalkaloids, which render the tubers green, bitter, and toxic [53]. These results indicate that application of 6–12 t ha^{-1} of rice residue (M1 to M4) induced more tuber greening and less yield compared to 14–16 t ha^{-1}, due to direct exposure of the potato tuber to sunlight at reduced mulch thickness. Thus, the limited thickness of mulch can be an obstacle in the formation and production of normal of tubers under PZTM. This study also highlighted that tuber yield decreased by 3–4 t ha^{-1} for every 2 t ha^{-1} reduction in rice straw mulch below the optimum rate (14–16 t ha^{-1}). Since trials 1, 2, and 4 were implemented with 12.5 t ha^{-1}, an amount that had been empirically determined to be sufficient based on observations in previous demonstration trials, it is likely that better yields could have been obtained in those trials if 14 t ha^{-1} had been applied.

Mulches can consist of organic plant materials, synthetic materials like plastic sheets, or any other material that minimizes soil evaporation and avoids high day/night temperatures that can penalize tuber yield. For potato, this is especially important during tuber initiation rather than during tuber bulking [51]. The type of mulch and the extent of soil surface coverage can significantly influence soil evaporation [54]. Mulching with neem leaf litter (M11) resulted in the highest potato yield and BCR among all treatments. This outcome may be attributed to favorable growing conditions, such as improved emergence, enhanced moisture and nutrient availability, regulated soil temperature, and reduced pest attacks, compared to other treatments [10]. The highest mulch costs observed in the M10 (jute mulch) and M9 (plastic mulch) treatments were attributable to the higher prices of jute and plastic materials. Among the treatments with paddy straw mulch, M7 (20 t ha^{-1}) and M8 (18 t ha^{-1}) were associated with the highest cultivation costs, reflecting that as the quantity of paddy straw increased, the cost of cultivation also rose. However, tuber yield significantly improved when the mulch quantity increased from 6 t ha^{-1} to 12 t ha^{-1}, with yield remaining similar beyond 12 t ha^{-1}. Consequently, the highest BCR achieved in M5 (14 t ha^{-1}) highlights the advantage of applying mulch rates close to the optimum level for maximizing economic returns.

4.4. Tighter plant spacing increases yield, but intermediate spacing optimizes profitability

Different plant spacing measures required varying quantities of seeds; narrower spacing allowed more plants to be planted per hectare. Consequently, the highest yield was achieved with spacing S1 (30 × 20 cm), while the lowest yield was recorded for the sparser plant density S9 (50 × 30 cm). Spacing S3 (40 × 20 cm) served as a control, as it matched the spacing used in the other trials, and its yield—one of the highest yields in Trial 3—demonstrated consistency across trials, with yields in the same range as those corresponding treatments in the other trials (F2, V12, and M5). Although narrower spacing (from S3 to S1) resulted in higher yields due to a greater number of plants per unit area, this intensification did not improve economic returns, as reflected in the reduced BCR, which was mainly driven by higher seed costs and smaller sizes of marketable tubers. The highest BCR observed at spacing S8 (50 × 20 cm) proved optimal, as it resulted from a balanced combination of intermediate yield, moderate seed costs, and improved marketable yield, collectively enhancing economic returns. Other studies have reported similar findings, indicating that optimal plant spacing maximizes net profit [55].

The addition of compost (S11) combined with the standard plant spacing (40 × 20 cm) appears to influence yield significantly, as demonstrated in Trial 1. While MY was similar across treatments, the lowest values were associated with the significantly lowest TY. Previous studies tested S9 (50 × 30 cm) under conventional tillage and found that TY could be increased by reducing the plant interval from 80 cm to 50 cm between rows and 30 cm within rows [56]. The varying amounts of seeds used for each treatment implied different seed costs, significantly affecting BCR between treatments for both seasons. Changing plant spacing or densities in potato crops has been a common practice for decades in many regions worldwide [57–59]. Although no ideal plant spacing exists, some configurations have yielded better results depending on the variety and market preferences for tuber size. Previous research indicated no significant difference between plant densities but showed a positive correlation with dry TY [56]. For example, a study on Andean potatoes in Peru adopted greater distances between plants to maximize foliage development, resulting in lower yields that could be attributed to the genetic potential of native potato landraces [60]. According to Beukema and van der Zag [61], high plant density can promote early tuber growth, leading to earlier maturation of the plants. Consequently, plant spacing should not be considered as a fixed parameter but rather as a management decision that requires adjustment to optimize both productivity and profitability.

4.5. Limitations, opportunities, and future directions in the adoption of PZTM for potato production

While rice straw availability is not a major constraint for PZTM in rice-potato systems, several other factors may limit its effectiveness. A significant limitation is the lack of access to improved, early-maturing varieties, which restricts yield potential and often results in suboptimal yields compared to conventional systems, as farmers typically rely on common local varieties not adapted to the less favorable growing conditions after rice [22,62]. In addition to the spread of diseases through degenerated seed tubers [22], PZTM also tends to be more vulnerable to rodent damage and crop losses from winter rainfall [62]. Addressing these challenges will require stronger seed systems, refined agronomic practices, and long-term evaluations across diverse environments, thereby enabling broader generalization of PZTM in rice-based systems.

On the other hand, PZTM represents not only an agronomic opportunity—such as a low-cost technology for crop intensification or long-term soil health improvements [20,22,62]—but also an underexplored opportunity for biotechnological valorization. Rice straw contains polysaccharides such as arabinoxylans, lignocellulosic biomass, and secondary metabolites, which can be valorized through fermentation and related bioprocesses [63]. Moreover, rice straw hydrolysates have been successfully employed in dark fermentation processes, including iron (magnetite)-assisted systems, to generate biohydrogen, and in low-nutrient fermentations such as tequila vinasse valorization [64]. Fermentation thus plays a fundamental role in converting an abundant by-product into biofertilizers, organic acids, bioenergy, and natural compounds [65]. Such applications could complement PZTM by creating additional value streams from an abundant by-product without compromising its primary role as mulch.

Future directions should prioritize scaling up PZTM through participatory approaches, including community nutrition scholars, farmer field schools, and similar extension models [21], as well as community videos, alongside promoting the adoption of improved early-maturing potato varieties [22]. Pilot-scale initiatives that combine agronomic optimization with community-level training could facilitate broader adoption and strengthen the sustainability of the practice. Thus, dissemination efforts have already highlighted the practice's impact, featuring farmers, scientists, and advocates from the International Potato Center discussing the transformative effects of zero-tillage and conservation agriculture on sustainable potato production in Asia [66].

5. Conclusions

The optimization of management practices for potato production using zero-tillage with rice straw mulch shows significant potential for sustainable and profitable potato cultivation. Combinations of organic and inorganic fertilizers, particularly F9 (i.e., 50 % RDF + 7.5 t ha^{-1} FYM + 2.5 t ha^{-1} VC), resulted in superior crop yields, profitability, and agronomic efficiency of nutrients compared to treatments using only inorganic or organic fertilizers. The *Kufri Khyati* variety and similar cultivars demonstrated exceptional adaptability to this production method, achieving marketable yields exceeding 30 t ha^{-1}. An optimal mulch thickness of 14–18 t ha^{-1} and a planting spacing of 50 × 20 cm maximized yield and BCR while minimizing issues such as greening and non-marketable tubers. The cost of mulch was included in this study to enable economic comparison between trials and treatments. However, given that rice mulch may not have market value due to over-abundant availability in many local contexts, the actual BCR in practice is likely to be significantly higher than that reported in this study. Furthermore, PZTM system effectively reduced the CF and GHG intensity, highlighting its environmental benefits. These findings emphasize the importance of integrating optimized agronomic practices with ecological considerations to enhance resource efficiency and sustainability in potato production in rice-based systems.

CRediT authorship contribution statement

Suresh K. Kakraliya: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **David A. Ramírez:** Writing – review & editing, Software, Resources. **Johan Ninanya:** Writing – review & editing, Visualization, Software, Formal analysis. **Cecilia Silva-Díaz:** Writing – original draft, Software, Formal analysis. **Brijesh Kumar:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Shiv P. Singh:** Writing – review & editing, Supervision. **Ajay Choudhary:** Writing – review & editing, Methodology, Investigation, Data curation. **Marcel Gatto:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Jan F. Kreuze:** Writing – review & editing, Supervision, Resources, Project administration.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2025.102345.

Data availability

Data will be made available on request.

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