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Coastal Salinity Management and Cropping System Intensification through Conservation Agriculture in the Ganges Delta

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Abstract: Soil salinity is the major constraint for cropping system intensification in the coastal region of the Ganges Delta. Salts build up on the soil surface, as well as in the crop root zone, due to the capillary rise in underground brackish water, hampering the growth and development of crops and resulting in mortality and low yields. We studied, for three years (2020–2021 to 2022–2023), the effect of conservation agricultural practices (zero tillage planting, crop residue recycling, and crop rotations) on the major soil properties (soil salinity and organic carbon status), crop performance (yield and economics), and water footprint. Conservation agricultural practices significantly reduce soil salinity, build soil organic carbon, reduce water footprint, and increase the profitability of cropping systems compared to tillage-intensive conventional practices. Under conventional agriculture, the sole cropping of rice is more profitable than double and triple cropping systems.

Keywords: coastal region; cropping system; economics; irrigation; salinity; water footprint

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1. Introduction

In the coastal region of the Ganges Delta, due to soil wetness after the harvesting of Kharif (monsoon/wet season) rice, the establishment of subsequent Rabi (post-monsoon/winter season) crop is delayed when conventional tillage is practiced [1]. Therefore, most of the land remains fallow during the Rabi and summer (pre-monsoon/dry season) periods [2]. For conventional tillage, soil is required to dry to reach the optimum moisture for ploughing. This process increases the time lag between Kharif and Rabi crops, resulting in the delayed sowing of Rabi crops following the harvesting of Kharif crops and a loss of carry-over soil moisture by evaporation and the build-up of salinity on the soil surface. To reduce the time lag and utilize the residual soil moisture, alternative tillage/crop establishment methods for Rabi crops are required. The scarcity of irrigation water and the salinity of soil and irrigation water are other constraints that restrict Rabi crop cultivation in coastal salt-affected areas [3,4]. Therefore, technology to reduce the irrigation water requirement and the effect of salinity on crops is required in coastal saline regions. Conservation agriculture practices involving zero/reduced tillage, the recycling of crop residues, and crop rotations are reported to reduce the time lag between Kharif and Rabi crops [5]. So, it is imperative to study the response of Rabi crops to conservation tillage practices in the coastal salt-affected areas, particularly with respect to crop geometry and the amount of crop residues.

A significant barrier to crop cultivation in coastal areas during the dry season is soil salinity [6]. However, many farmers in the Ganges Delta region who have access to irrigation find dry-season cultivation profitable. Boro rice is grown by several farmers in this region who have access to groundwater irrigation, with a significant investment of irrigation water (>130 cm) and reduced irrigation water productivity (IWp) of 31–35 kg ha^{-1}cm^{-1} [7]. An increase in Boro rice area necessitates a growing number of shallow tube wells, with the negative consequences of the rapid withdrawal of freshwater from the aquifer and ingress of saline water resulting in an accelerated soil salinization process. According to current research [8–10], conservation agriculture (CA) practices increase yield with less inputs. During the monsoon season, rice is the main crop in the Ganges Delta region. This crop produces a significant amount of straw and retains soil moisture for the next season. But under normal practice, tillage is challenging because of too much moisture.

Soil's physical characteristics are negatively impacted by heavy tillage operations [11], which also reduce the soil organic carbon status [12]. Compared to conventional puddle transplanted rice and conventional tillage in wheat/maize, the beneficial changes in soil characteristics that resulted from conservation tillage and crop residue retention led to higher crop production [13]. Across several agro-ecological zones, zero-tillage (ZT) techniques produced a substantial yield boost over conventional tilled wheat, even in the absence of complete residue retention. In the Eastern Indo-Gangetic plains, ZT average yield gains of around 498 kg ha^{-1} (19%) have been reported [14]. By implementing ZT technology, India's mono-cropped coastal saline land can be transformed into double and triple cropping situations. This unique technology has the double benefits of climate change mitigation and economic gains, suggesting a win-win situation for the farming community [15]. Since climate change's effects on agriculture are especially relevant in low-lying coastal areas [16], it is imperative to adopt innovative practices to adapt under changed situations. Coping strategies under such situations need to focus on sustainable intensification options such as the conservation of soil moisture, rainwater harvesting, conservation tillage, early crop establishment, crop residue recycling, and minimal greenhouse gases' (GHGs) emission, as these ensure profitability and positive effects on soil health and the environment [1].

Globally, the studies on CA practices are concentrated in non-saline areas, and in India, they are mostly focused on rice–wheat production systems [17–19]. Further, studies on the practices of CA in coastal salt-affected soil are very scant and cropping-system-based recommendations of CA have not been delineated. In non-saline areas, CA has been shown to have a number of advantages, such as increased yields, a more efficient use of nutrients, the conservation of soil moisture, saving irrigation water, a reduction in land degradation, a reduction in the adverse effects of climate change, an improved air quality, an increased biodiversity, including agrobiodiversity, and an improved water quality [20–24]. CA practices, such as zero-tillage planting with paddy straw mulching practiced for potato crop in coastal saline soils, help in the conservation of soil moisture, reduction in irrigation water use, restriction of salinity build up, and improvement in crop quality [1]. The adoption of CA also has several benefits for maintaining the soil physico-chemical and biological properties, ensuring ecosystem services and food security [25]. However, responses to conservation agriculture practices vary with crops and for the same crop, and the packages of practices vary for conventional and conservation tillage practices. Therefore, there is a great need to standardize CA practices for different cropping systems in coastal saline soils. Keeping the above facts in view, the present study was conducted with the hypotheses that (i) conservation tillage helps in the early sowing of Rabi crops, thus utilizing the residual soil moisture and reducing the irrigation water requirement, (ii) paddy straw mulching will reduce soil salinity build-up during the Rabi season, and (iii) zero tillage will increase crop yield with less use of inputs.

2. Materials and Methods

2.1. Study Site

This study was conducted at the research farm of ICAR—Central Soil Salinity Research Institute, Regional Research Station, Canning Town (22°15′ N, 88°40′ E; 3.0 m amsl), West

Bengal, during three cropping cycles (Kharif–Rabi–summer) each year for 2020–2021, 2021–2022, and 2022–2023 (nine cropping seasons). The experimental site is characterized by a fine-textured clayey (Table 1) soil with a mean bulk density of 1.47 g cm^{-3}, neutral pH (7.29), an initial soil salinity (ECe) ranging from 1.99 to 4.40 dS m^{-1}, low organic carbon (0.43%) and available nitrogen (177.7 kg ha^{-1}), medium available phosphorus (17.5 kg ha^{-1}), and high available potassium (293.1 kg ha^{-1}).

Table 1. Initial (November 2020) soil properties of the experimental site at Canning Town.

Parameters	Procedure	Mean	Range
BD (g cm^{-3})	Core sampler	1.47	1.40–1.52
pH (1:2)	Soil: water	7.29	7.05–7.44
ECe (dS m^{-1})	Saturation extract	2.81	1.99–4.40
Microbial population (CFU g^{-1} soil)	Dilution plate method in Nutrient Agar plate	1.89 × 10^6	1.625–2.15 × 10^6
Sand (%)	Bouyoucos hydrometer	22.5	21.1–24.3
Silt (%)		31.6	30.1–32.5
Clay (%)		45.9	43.3–47.3
N (kg ha^{-1})	Alkaline potassium permanganate method	177.7	165.9–201.3
P (kg ha^{-1})	Olsen method	17.5	14.1–21.6
K (kg ha^{-1})	Flame photometric method	293.1	285.5–303.9
OC (%)	Walkley and Black	0.43	0.40–0.47

The climate of the study location is sub-humid tropical with an average annual rainfall of 1680 mm and an average monthly temperature varying from 19.7 °C in January to above 30.1 °C in May (Figure 1). The Kharif season spans from June–July to November–December, the Rabi season from November–December to February–March, and the summer season from February–March to April–May. The Kharif rainfall during 2020–2021, 2021–2022, and 2022–2023 was 1323, 2751, and 1240 mm, respectively (Figure 1).

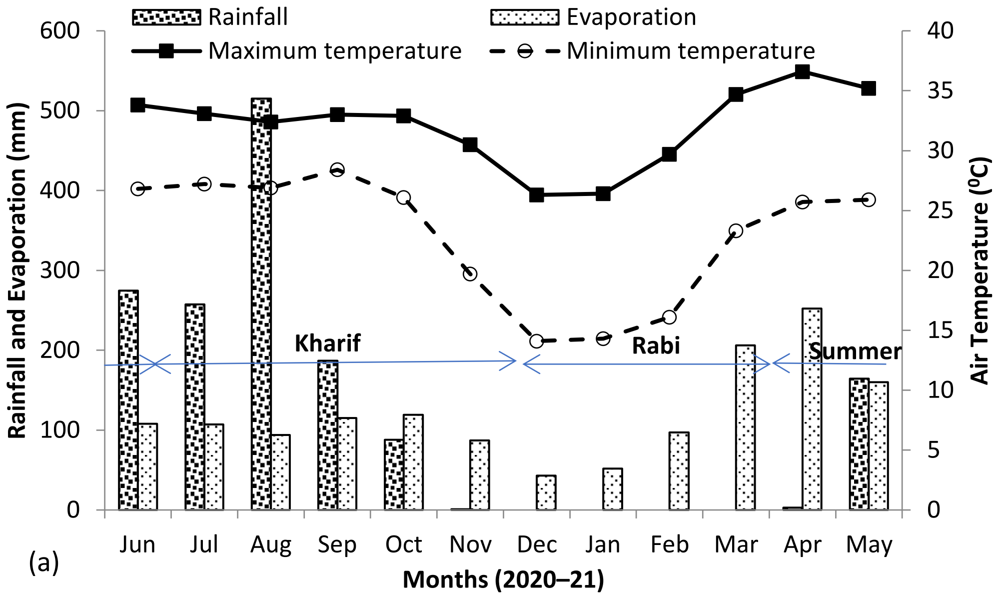

Figure 1. *Cont.*

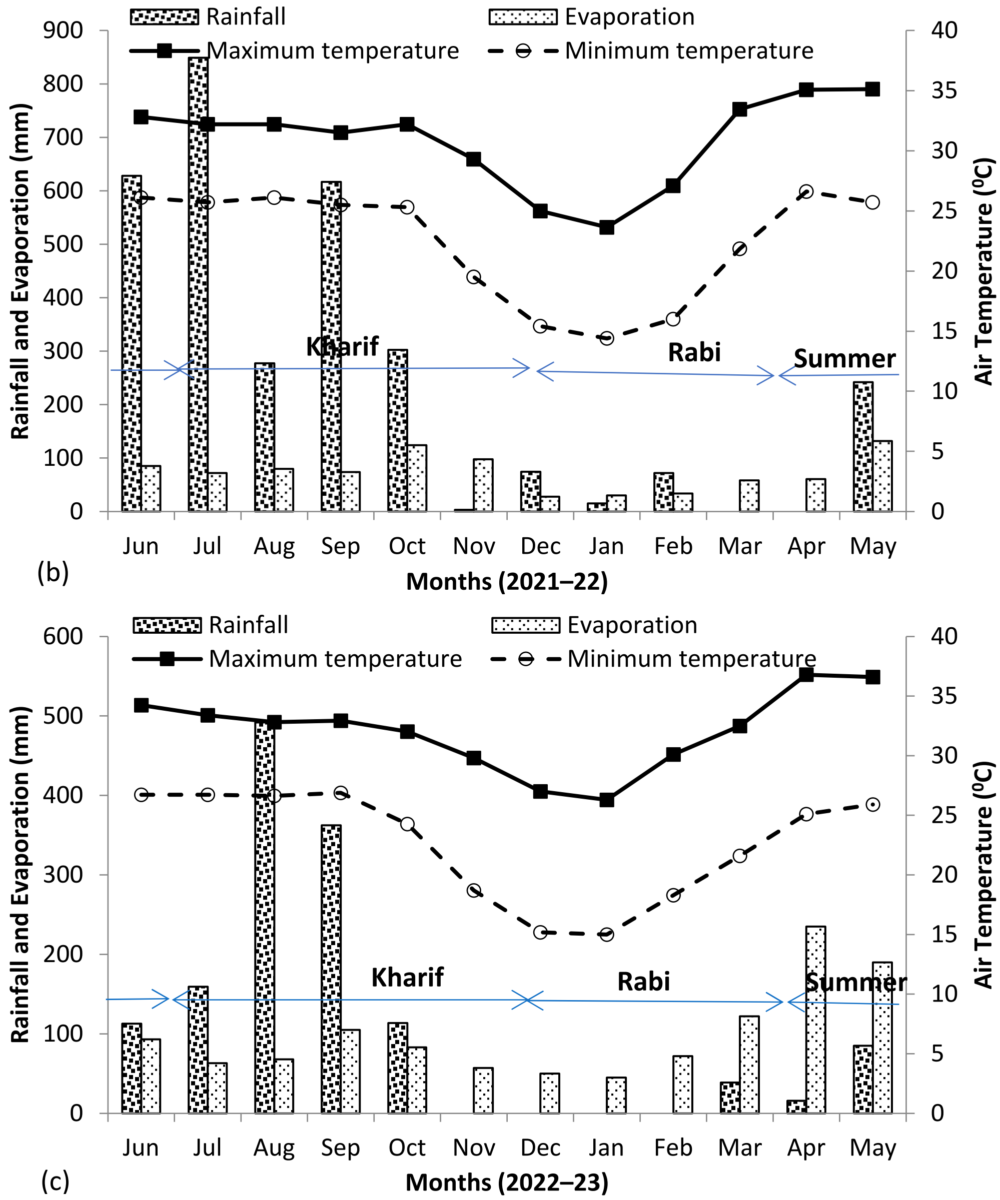

Figure 1. Weather data (rainfall, maximum, and minimum temperatures) of the study site during the crop growing period (**a**) 2020–2021, (**b**) 2021–2022, and (**c**) 2022–2023.

2.2. Experimental Details

Experiments were conducted on three cropping systems, *viz.* rice–potato–green-gram, rice–mustard–green-gram, and rice–garlic–green-gram. In each cropping system, there was a control treatment of conventional practices and nine conservation agriculture treatments with different Rabi crop geometries and amounts of crop residues (treatment details are given in Table 2). Rice crop residue (straw) was used as mulch in the next crop and green gram stover was left in the field for all the conservation treatments. In the conventional practice, all the crop residues were removed from the system.

The experimental design was randomized block, with each treatment replicated thrice. In the conventional practice, primary and secondary tillage operations were carried out when the soil attained the optimum moisture and all the crop residues were removed from the system. For the conservation treatments, zero-tillage (ZT) planting was performed immediately after the harvesting of Kharif paddy, straw was used as mulch for the Rabi crops, and green gram stover was left in the field. In case of ZT planting, farmyard manure (FYM) was used to cover the tubers/seeds/cloves, followed by the basal fertilizer application, and then paddy straw mulching was performed, as per the treatments. Conventional tillage required initial irrigation, whereas, in the case of ZT planting, no irrigation was required during and after planting, as the soil was wet enough for germination. Subsequent irrigations were given at 50% depletion of the available soil moisture.

Table 2. Treatment details for experiment on three cropping systems in the salt-affected soils of the Ganges Delta.

Cropping System	Treatment Details
Rice–potato–green-gram	(1) Control (conventional tillage for ridge and furrow planting of potato, no crop residue recycling/mulching) (2) Zero-tillage (ZT) planting of potato with 30 × 15 cm crop geometry and 9 t ha^{-1} paddy straw mulching (PSM) (3) ZT planting of potato with 30 × 15 cm crop geometry * and 12 t ha^{-1} PSM (4) ZT planting of potato with 30 × 15 cm crop geometry and 15 t ha^{-1} PSM (5) ZT planting of potato with 45 × 15 cm crop geometry and 9 t ha^{-1} PSM (6) ZT planting of potato with 45 × 15 cm crop geometry and 12 t ha^{-1} PSM (7) ZT planting of potato with 45 × 15 cm crop geometry and 15 t ha^{-1} PSM (8) ZT planting of potato with 60 × 15 cm crop geometry and 9 t ha^{-1} PSM (9) ZT planting of potato with 60 × 15 cm crop geometry and 12 t ha^{-1} PSM (10) ZT planting of potato with 60 × 15 cm crop geometry and 15 t ha^{-1} PSM
Rice–mustard–green-gram	(1) Control (conventional tillage for ridge and furrow planting of mustard, no crop residue recycling/mulching) (2) ZT planting of mustard with 20 × 10 cm crop geometry and 2 t ha^{-1} paddy straw mulching (PSM) (3) ZT planting of mustard with 20 × 10 cm crop geometry and 4 t ha^{-1} PSM (4) ZT planting of mustard with 20 × 10 cm crop geometry and 6 t ha^{-1} PSM (5) ZT planting of mustard with 25 × 10 cm crop geometry and 2 t ha^{-1} PSM (6) ZT planting of mustard with 25 × 10 cm crop geometry and 4 t ha^{-1} PSM (7) ZT planting of mustard with 25 × 10 cm crop geometry and 6 t ha^{-1} PSM (8) ZT planting of mustard with 30 × 10 cm crop geometry and 2 t ha^{-1} PSM (9) ZT planting of mustard with 30 × 10 cm crop geometry and 4 t ha^{-1} PSM (10) ZT planting of mustard with 30 × 10 cm crop geometry and 6 t ha^{-1} PSM
Rice–garlic–green-gram	(1) Control (conventional tillage for ridge and furrow planting of garlic, no crop residue recycling/mulching) (2) ZT planting of garlic with 20 × 10 cm crop geometry and 3 t ha^{-1} paddy straw mulching (PSM) (3) ZT planting of garlic with 20 × 10 cm crop geometry and 5 t ha^{-1} PSM (4) ZT planting of garlic with 20 × 10 cm crop geometry and 7 t ha^{-1} PSM (5) ZT planting of garlic with 25 × 10 cm crop geometry and 3 t ha^{-1} PSM (6) ZT planting of garlic with 25 × 10 cm crop geometry and 5 t ha^{-1} PSM (7) ZT planting of garlic with 25 × 10 cm crop geometry and 7 t ha^{-1} PSM (8) ZT planting of garlic with 30 × 10 cm crop geometry and 3 t ha^{-1} PSM (9) ZT planting of garlic with 30 × 10 cm crop geometry and 5 t ha^{-1} PSM (10) ZT planting of garlic with 30 × 10 cm crop geometry and 7 t ha^{-1} PSM

* Crop density for potato with spacings of 30 × 15, 45 × 15, and 60 × 15 cm corresponds to 2.22, 1.48, and 1.11 lakhs ha^{-1}, respectively, and for mustard, as well as that for garlic spacings of 20 × 10, 25 × 10, and 30 × 10 cm corresponds to 5.00, 4.00, and 3.33 lakhs ha^{-1}, respectively.

The specifics of the crop schedule and main inputs utilized in the field study are given in Table 3. Rice cultivar 'Swarna-Sub 1' was used during the Kharif experiment, with a maturity period of 140–145 days. The Odisha State Seed Sub-Committee of Agricultural Crops released this rice variety in 2009 for adoption in coastal lowland areas [26]. It can be planted late with older seedlings and can withstand total submersion for a period of up to 17 days. The adoption of Swarna-Sub 1 under flooded conditions results in additional yield and income of around 19 and 48%, respectively [27]. The potato cultivar 'Kufri Pukhraj' is an early-maturing (70–90 days), nutrient-rich (excellent source of vitamin C, potassium, and fiber), and disease-tolerant (late blight and sclerotium wilt) variety suitable for coastal regions. The mustard variety 'DRMR 150-35', an early-maturing (114 days) variety recommended for eastern India under early-sown rainfed conditions with a tolerance to powdery mildew and blight diseases, was used. 'Yamuna Safed' used in this study is a short-day garlic cultivar with a maturity duration of 140–150 days, notified by the government of India for cultivation all over the country. The local variety of green gram known as 'Chaity Mung' was grown during the summer season, in which pods start maturing from about 60 days. The grain and straw yields of rice, the tuber and haulm yields of potato, the seed and stover yields of mustard, and the bulb and residue yields of garlic from each plot were recorded, and yield data were converted to tons per ha (t ha^{-1}). Data on input requirements, such as human and machine labor, fuel use, irrigation water, crop protection inputs, and manures and fertilizers, were recorded. Soil salinity as the electrical conductivity of the saturation extract (ECe) of the topsoil (0–20 cm) was observed in all the plots on a monthly basis. The soil salinity was determined as the electrical conductivity of the saturation extract—ECe [28]—in dS m^{-1} using a digital electrical conductivity meter (Systronics India Ltd., Ahmedabad, Gujarat, India). The sole (noted as rice–fallow), double (rice–potato, rice–mustard, and rice–garlic), and triple (rice–potato–green-gram, rice–mustard–green-gram, and rice–garlic–green-gram) cropping systems' performances were evaluated in terms of rice equivalent yield (REY), cost of cultivation, gross return, and net return and benefit cost ratio (BCR).

Table 3. Calendar of operations for different crops and major inputs used in three different cropping systems during 2020–2023.

Particulars	Year	Kharif Rice	Potato	Mustard	Garlic	Green Gram *
Variety	2020–2023	Swarna-Sub1	Kufri Pukhraj	DRMR 150-35	Yamuna Safed	Local
Seed rate	2020–2023	45 kg ha^{-1}	1.5–1.8 t ha^{-1}	5–6 kg ha^{-1}	0.50–0.75 t ha^{-1}	20–25 kg ha^{-1}
Date of sowing/planting	2020–2021	21 June 2020	ZT: 26 November 2020 Conv: 7 December 2020	ZT: 26 November 2020 Conv: 7 December 2020	ZT: 26 November 2020 Conv: 7 December 2020	ZT: 25 February 2021 Conv: 13 March 2021
	2021–2022	6 June 2021	ZT: 10 November 2021 Conv: 27 December 2021	ZT: 10 November 2021 Conv: 27 December 2021	ZT: 10 November 2021 Conv: 27 December 2021	ZT: 13 February 2022 Conv: 5 March 2022
	2022–2023	10 June 2022	ZT: 3 November 2022 Conv: 23 December 2022	ZT: 3 November 2022 Conv: 23 December 2022	ZT: 3 November 2022 Conv: 23 December 2022	ZT: 7 February 2023 Conv: 23 March 2023
Date of harvesting	2020–2021	23 November 2020	ZT: 9 February 2021 Conv: 3 March 2021	ZT: 19 February 2021 Conv: 10 March 2021	ZT: 24 March 2021 Conv: 7 April 2021	ZT: 27 April 2021 Conv: 15 May 2021
	2021–2022	7 November 2021	ZT: 10 February 2022 Conv: 13 March 2022	ZT: 12 February 2022 Conv: 1 March 2022	ZT: 10 March 2022 Conv: 3 April 2022	ZT: 22 April 2022 Conv: 9 May 2022
	2022–2023	1 November 2022	ZT: 7 February 2023 Conv: 23 March 2023	ZT: 1 February 2023 Conv: 15 March 2023	ZT: 3 March 2023 Conv: 10 April 2023	ZT: 11 April 2023 Conv: 27 May 2023
Manure (FYM) used (t ha^{-1})	2020–2023	10	5	5	5	-
Paddy straw recycled (t ha^{-1})	2020–2023	-	9–15 (season^{-1})	2–6 (season^{-1})	3–7 (season^{-1})	-
Chemical fertilizer (N-P-K) used (kg ha^{-1})	2020–2023	60–40–40	100–75–75	40–20–20	75–40–40	12.5–25–12.5

ZT: zero-tillage planting; Conv: conventional tillage planting; * Dates for rice–potato and rice–mustard systems; in rice–garlic system, the sowing and harvesting of green gram was delayed by about one month as the maturity duration of garlic was more than potato and mustard.

2.3. Determination of Crops' and Cropping Systems' Yield

The economic yields of different crops (rice—grain and straw; potato—tubers; mustard—seed; garlic—bulb; green gram—seed and stover) were recorded in kg at maturity from three 1 m^2 quadrats chosen randomly from three locations in each plot, and converted to t ha^{-1} by using the area (1 ha = 10,000 m^2) and weight (1 ton = 1000 kg) conversion factors. The yield of individual crops was converted to rice-equivalent yield (REY) by the use of yield and the prevailing market price of respective produce.

REY = (Y1P1 + Y2P2 + Y3P3)/Pr, where Y1, Y2, and Y3 are the yields of crops 1, 2, and 3, respectively; P1, P2, and P3 are the prices of crops 1, 2, and 3, respectively; and Pr is the price of rice. For the double and triple cropping systems, the REYs of individual crops were added to obtain the REY for the cropping system.

2.4. Determination of Soil Organic Carbon Status

The modified Walkley and Black method was used to analyze the C fractions in the soil [29]. The procedure involved the use of 5, 10, and 20 mL of concentrated H_2SO_4 to produce acid aqueous medium with three ratios (0.5:1, 1:1, and 2:1), which produced solutions of graded normality of H_2SO_4, i.e., 12, 18, and 24 N, respectively. The use of 20 mL of H_2SO_4 corresponded to the original wet oxidation method [30]. Further, 10 mL of 1 N potassium dichromate (KCr_2O_7) solution served as an oxidizer for 1 of g soil, and after that, the dilution of the mixture was conducted with 200 mL of water. Then, 10 mL of H_3PO_4 was mixed. The excess $Cr_2O_7{}^{2-}$ was titrated with 0.5 N ferrous ammonium sulfate [$Fe(NH_4)_2(SO_4)_2.6H_2O$]. This process resulted in four distinct C fractions (Cfrac1, Cfrac2, Cfrac3, and Cfrac4). Very-labile fraction (Cfrac1) was part of the organic C oxidized under 12 N H_2SO_4. Labile fraction (Cfrac2) represented the organic C oxidized in 18 N H_2SO_4 minus the organic C oxidized in 12 N H_2SO_4. Less-labile fraction (Cfrac3) was the organic C oxidized in 24 N H_2SO_4 minus the organic C oxidized in 18 N H_2SO_4. Non-labile fraction (Cfrac4) was the total SOC (TOC) minus the organic C oxidized in 24 N H_2SO_4. TOC was determined by a CHN analyzer.

For simple presentation, the total of very-labile (Cfrac1) and labile fractions (Cfrac2) was denoted as the active C-pool. Similarly, the sum of less-labile (Cfrac3) and non-labile fractions (Cfrac4) indicated a passive C-pool. The lability index (LI) was calculated by using the very-labile, labile, and less-labile fractions of the total SOC, assigning weighting factors of 3, 2, and 1 to Cfrac1, Cfrac2, and Cfrac3, respectively [31,32]. The following formulae were used to calculate the LI, carbon pool index (CPI), and carbon management index (CMI).

$$\text{LI} = [(\text{very labile C}/\text{TOC}) \times 3 + (\text{labile C}/\text{TOC}) \times 2 + (\text{less labile C}/\text{TOC}) \times 1]$$

$$\text{CPI} = \text{Sample TOC (g kg}^{-1})/\text{TOC (g kg}^{-1}) \text{ under conventional system}$$

$$\text{CMI} = \text{CPI} \times \text{LI} \times 100$$

2.5. Determination of Water Footprint

The water footprint of a product (m^3 unit^{-1}) was calculated as the ratio of the total volume of water used (m^3 year^{-1}) to the quantity of the production (ton year^{-1}) [33]. In our study, the production was taken from REY data (as explained in 2.3 above). For Kharif rice (a rainfed crop), the volume of water use was estimated by adding 300 mm of percolation loss [33] to the actual evaporation loss during the crop-growing period in each year. The actual amounts of irrigation water applied during the Rabi (potato, mustard, and garlic) and summer (green gram) seasons for respective crops were used for the estimation of the water footprint.

2.6. Economics and Statistical Analysis

For evaluation of the economic performance of the cropping systems, the costs and returns of individual crops were added as per the cropping system, e.g., in the rice–potato–green-gram system, the respective data for rice, potato, and green gram were added to estimate the economic parameters. The data on economics (costs and returns) were calculated based on the prevailing market prices of inputs, labor, and produce in Indian rupees (₹) during 2020–2023. These replicated data were converted into USD ha^{-1} by using the currency conversion rates (1 USD = INR 74, 79, and 83 during 2020–2021, 2021–2022, and 2022–2023, respectively). The cost of cultivation was calculated based on the prevailing market prices of the various inputs used in the experiment. The input costs involved the costs of seed tubers, compost, chemical fertilizers, fungicides, irrigation, and field preparation. The human labor employed for all operations, such as planting, the distribution of paddy straw as mulch, the application of compost over the seed tubers, fertilizers, fungicides, irrigation water, and harvesting, was determined in person–days ha^{-1}, where 8 h makes up a working day. Multiplication of the yield (t ha^{-1}) with the market price of tubers (INR t^{-1}) gave the value for gross return (INR ha^{-1}). Net return was obtained by subtracting the cost of cultivation from the gross return, and the ratio of gross return to the cost of cultivation resulted in the benefit–cost ratio (BCR).

The treatment-wise replicated data were used for analysis of variance (ANOVA) using the Statistical Tool for Agricultural Research (STAR version 1.0) software developed by the International Rice Research Institute (IRRI), Manila, Philippines [34]. The ANOVA for different parameters are given in Table S1. The significance of the treatment means' differences were observed by the use of least significant difference (LSD) values obtained by multiplying the standard error of the mean difference with the student's *t*-value using error degrees of freedom at a 5% level of significance [35].

3. Results

3.1. Soil Salinity

Month-wise soil salinity data for all the cropping systems were analyzed for determining the relation between the amounts of paddy straw recycling and the extent of soil salinity build-up during the dry season. In the control plots, the soil salinity varied from 3.3 dS m^{-1} during December 2020 to 9.2 dS m^{-1} during May 2021, whereas in the paddy straw mulched plots, it declined, and the lowest was observed with the highest level of mulching, with range from 1.38 dS m^{-1} during December 2020 to 4.45 dS m^{-1} during May 2021. Soil salinity (ECe) had a negative correlation ($r = -0.73$ **) with the amount (t ha^{-1}) of paddy straw mulching during the Rabi season (Figure 2a). In the control plots, soil salinity varied from 2.70–4.05 dS m^{-1} during December 2021 to 11.82–15.08 dS m^{-1} during May 2022, whereas in the paddy straw mulched plots, soil salinity development was restricted, and the lowest was observed with the highest level of mulching. The soil salinity with 15 t ha^{-1} paddy straw mulching was in the range from 1.03–2.07 dS m^{-1} during December 2021 to 3.79–5.19 dS m^{-1} during May 2022 (Figure 2b). Soil salinity increased with progress of the Rabi/summer season, with the highest soil salinity of 15.55 dS m^{-1} occurring during the month of May 2023 under the control treatment (no mulching), and the lowest of 3.68 dS m^{-1} with the paddy straw mulching of 15 t ha^{-1} (Figure 2c). Soil salinity (ECe) had a negative correlation ($r = -0.90$ **) with the amount (t ha^{-1}) of paddy straw mulching during the Rabi season (Figure 2).

3.2. Weed Biomass

A significant ($p < 0.001$) effect of paddy straw mulching was observed on the weed biomass in the Rabi season crops. During 2020–2021, in the control plots (without mulching or conventional tillage), the weed biomass was 1.91 g m^{-2}, 6.75 g m^{-2}, and 12.53 g m^{-2} for the mustard, potato, and garlic crops, respectively. With paddy straw mulching, the weed biomass was reduced to 0.47 g m^{-2}, 0.38 g m^{-2}, and 1.31 g m^{-2} in the respective crops (Figure 3). During the second year in the control plots (without mulching or conventional tillage), the weed biomass was 1.89 g m^{-2}, 8.33 g m^{-2}, and 34.95 g m^{-2} in the mustard, potato, and garlic crops, respectively. With paddy straw mulching, the weed biomass was reduced to 0.44 g m^{-2}, 3.30 g m^{-2}, and 12.00 g m^{-2} in the respective crops (Figure 3). The mulching of paddy straw also suppressed the growth of weeds in all crops during the third year, 2022–2023 (Figure 3). However, the weed density was higher in the garlic crop compared to potato and mustard in all the three years.

3.3. Soil Organic Carbon Status

The soil carbon statuses of the rice-based cropping systems in the coastal saline region under conventional and conservation agricultural practices were determined during 2021–2022 and 2022–2023. The soil C-pool was enriched due to conservation agriculture involving zero-tillage planting, rice crop residue recycling, and green gram in rotation. Conventional agricultural practices were unfavorable for soil carbon enrichment (Figure 4).

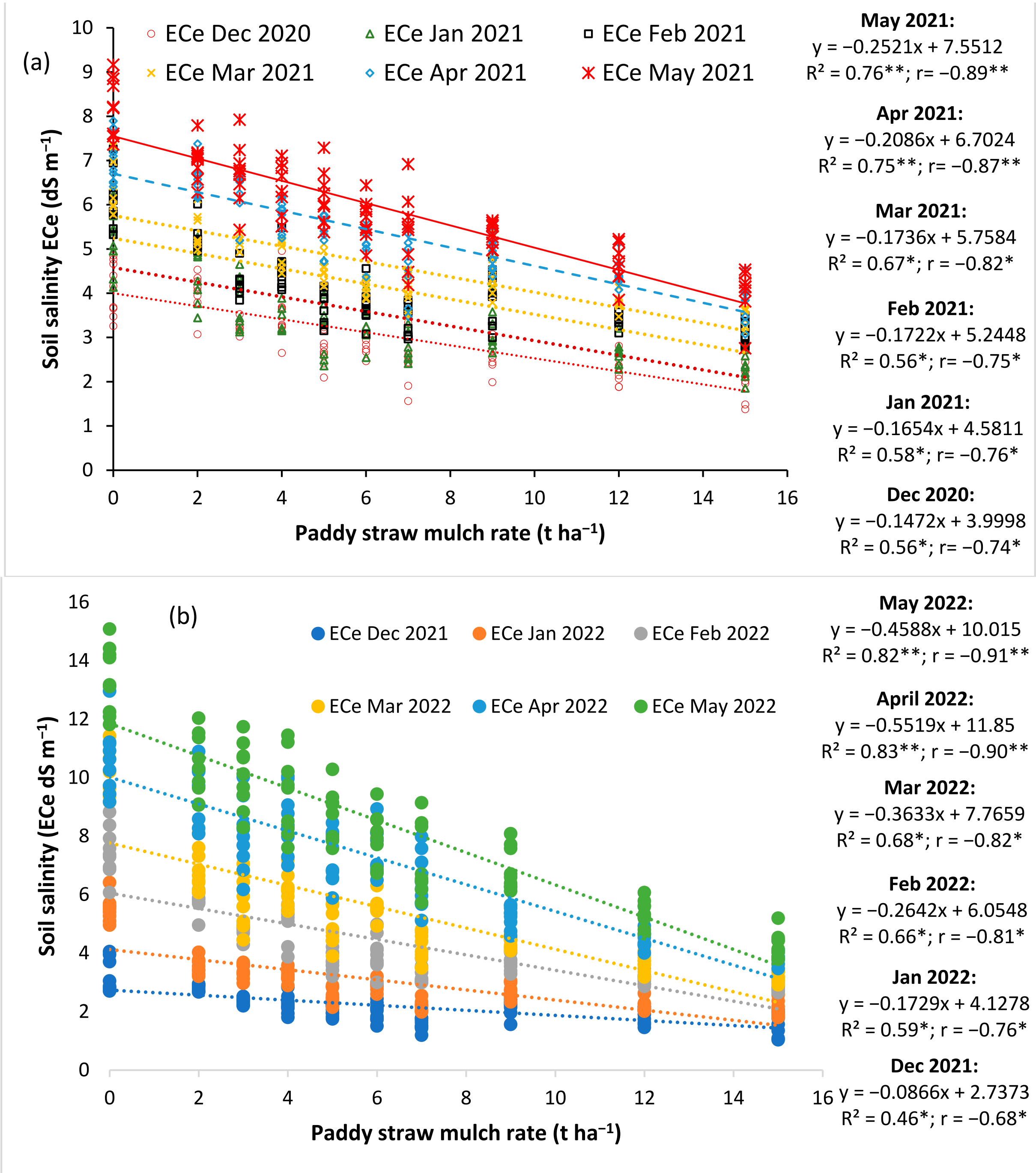

Figure 2. *Cont.*

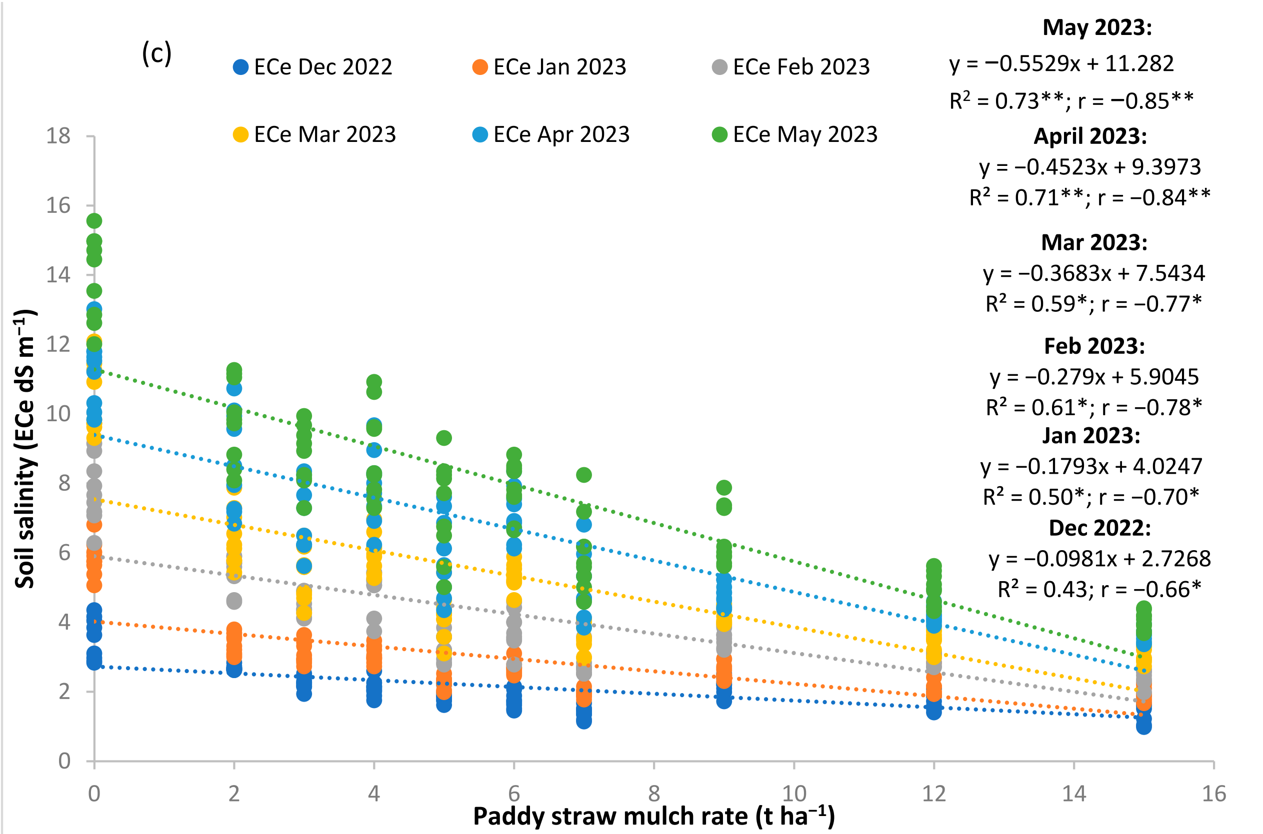

Figure 2. Effect of paddy straw mulching/residue retention on the soil salinity build-up in the subsequent Rabi seasons during: (**a**) December 2020–May 2021; (**b**) December 2021–May 2022, and (**c**) December 2022–May 2023. * significant at $p < 0.05$ and ** significant at $p < 0.001$.

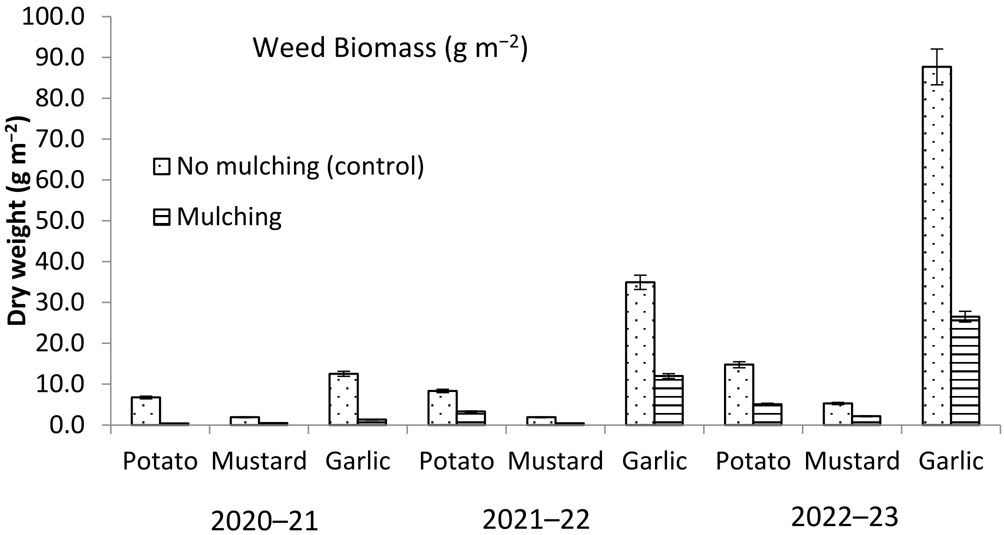

Figure 3. Effect of paddy straw mulching/residue retention on the weed biomass in subsequent Rabi crops during 2020–2021, 2021–2022, and 2022–2023. Data are mean over replications, crop geometry, and mulch rates. Columns with different lowercase alphabets are significantly different.

After the second year of the experiment (six crop cycles), during 2021–2022, the total organic carbon (TOC) under conventional practices varied from 4.51 to 4.78 g kg^{-1} soil, whereas in the conservation agricultural practices, it was 4.65–5.38 g kg^{-1} soil (Figure 4). After the third year (nine crop cycles) of the study during 2022–2023, the TOC in conventional agriculture declined to 4.11–4.36 g kg^{-1} soil, whereas it increased to 4.98–6.14 g kg^{-1}

under the conservation agricultural practices. Similarly, the LI, CPI, and CMI also increased under the conservation agricultural practices.

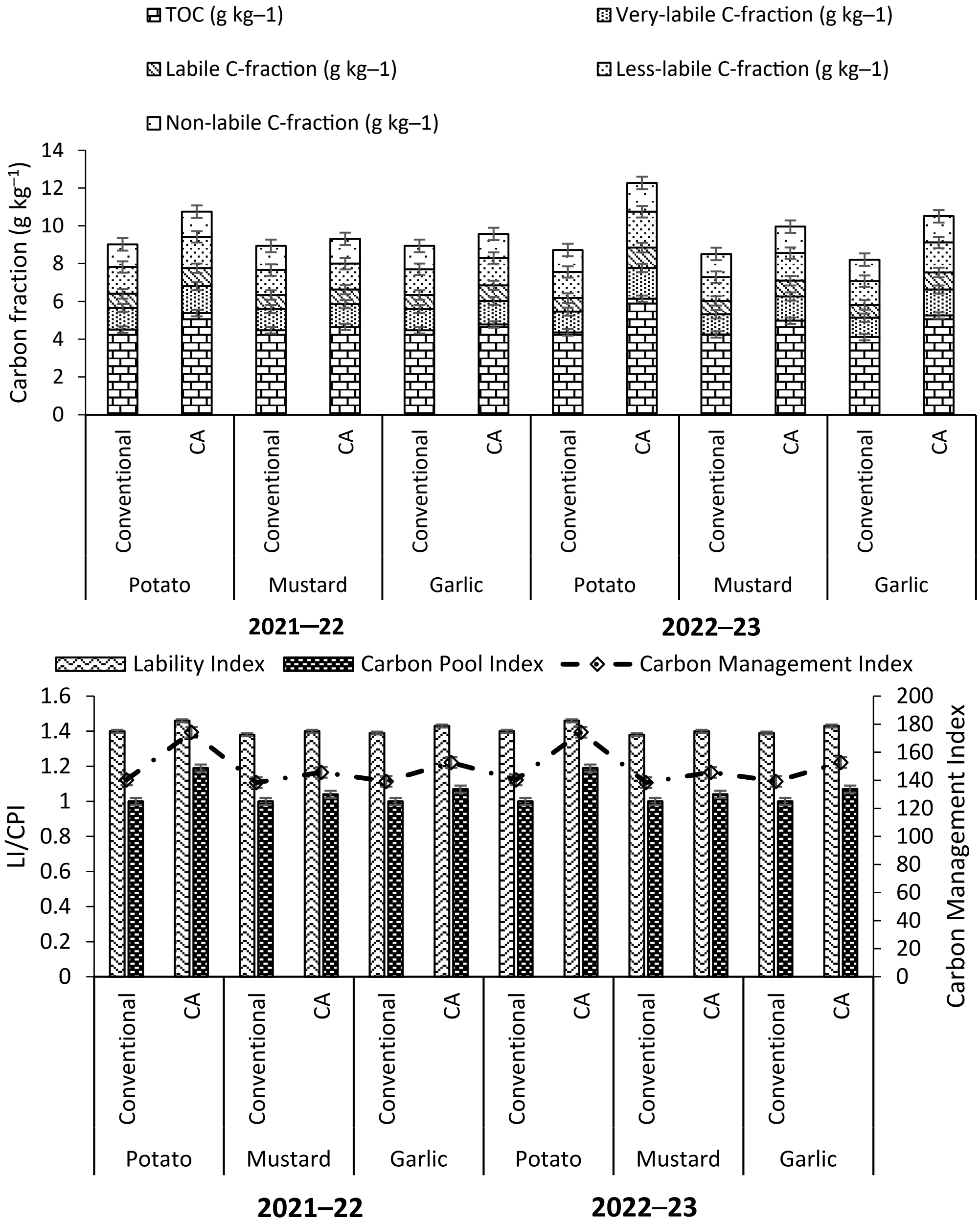

Figure 4. Soil organic carbon fractions, lability index, carbon pool index, and carbon management index under conventional and conservation agricultural (CA) practices in coastal saline soils during 2021–2022 and 2022–2023. Data are mean over replications, crop geometry, and mulch rates. Vertical lines in a bar show the standard error of means.

3.4. Yield and Economics

3.4.1. Yield of Rabi and Summer Crops

The yields of the Rabi (potato, mustard, and garlic) crops and succeeding green gram were significantly ($p < 0.05$) affected by geometry (row and plant spacings) and the amount of paddy straw recycled. In the case of potato in all three years, the tuber yield was significantly ($p < 0.001$) higher in the case of conservation agricultural practices involving ZT planting, paddy straw recycling, and closer spacing (Table 4). The seed yield of the succeeding green gram crop after potato was also positively affected due to crop residue recycling and conservation tillage (ZT). In all the years except in the third year

(2022–2023) after garlic, a significantly ($p < 0.05$) higher seed yield of green gram crop was observed under conservation agricultural practices compared to the conventional method of cultivation. In mustard crop, ZT planting with the recycling of paddy straw (4–6 t ha^{-1}) produced a significantly higher seed yield ($p < 0.05$ in 2020–2021 and $p < 0.001$ in 2021–2022 and 2022–2023) compared to the conventional agricultural practices (Table 5). A similar effect on the succeeding green gram crop after mustard was also observed. The mean bulb yield of garlic was more than 5 t ha^{-1} when 5–7 t ha^{-1} of paddy straw was recycled as mulch (Table 6). The seed yield of green crop after garlic was lower (0.16–0.41 t ha^{-1}) compared to that obtained after potato (0.32–1.04 t ha^{-1}) and mustard (0.31–0.83 t ha^{-1}).

Table 4. Yield of potato and succeeding green gram under different tillage, crop geometry, and residue amounts during Rabi 2020–2021, 2021–22 and 2022–2023.

Treatments for Potato Cultivation	**Tuber Yield (t ha^{-1}) of Potato**			**Seed Yield (t ha^{-1}) of Green Gram**		
	2020–2021	**2021–2022**	**2022–2023**	**2020–2021**	**2021–2022**	**2022–2023**
Conventional tillage for ridge and furrow planting of potato, no crop residue recycling	14.48 ^{c} ±0.99	11.16 ^{e} ±1.63	11.19 ^{f} ±2.19	0.4 ^{c} ±0.04	0.36 ^{e} ±0.03	0.32 ^{c} ±0.01
Zero-tillage (ZT) planting with 30 × 15 cm crop geometry and 9 t ha^{-1} paddy straw mulching (PSM)	21.74 ^{ab} ±6.20	17.08 ^{d} ±3.00	20.74 ^{d} ±3.95	0.58 ^{bc} ±0.11	0.64 ^{d} ±0.04	0.54 ^{b} ±0.06
ZT planting with 30 × 15 cm crop geometry and 12 t ha^{-1} PSM	23.31 ^{a} ±2.33	25.34 ^{ab} ±0.39	28.21 ^{a} ±1.79	0.64 ^{ab} ±0.07	0.81 ^{bc} ±0.09	0.56 ^{b} ±0.05
ZT planting with 30 × 15 cm crop geometry and 15 t ha^{-1} PSM	22.75 ^{a} ±0.54	26.54 ^{a} ±2.29	28.46 ^{a} ±0.56	0.61 ^{b} ±0.16	0.87 ^{b} ±0.05	0.64 ^{ab} ±0.09
ZT planting with 45 × 15 cm crop geometry and 9 t ha^{-1} PSM	16.90 ^{bc} ±2.70	16.24 ^{cd} ±0.38	18.32 ^{e} ±0.47	0.60 ^{b} ±0.08	0.67 ^{cd} ±0.16	0.57 ^{b} ±0.09
ZT planting of potato with 45 × 15 cm crop geometry and 12 t ha^{-1} PSM	18.30 ^{b} ±1.29	22.94 ^{b} ±3.11	23.01 ^{c} ±2.38	0.65 ^{a} ±0.10	0.94 ^{ab} ±0.06	0.77 ^{a} ±0.16
ZT planting with 45 × 15 cm crop geometry and 15 t ha^{-1} PSM	18.63 ^{b} ±3.10	26.12 ^{a} ±4.34	26.02 ^{ab} ±1.94	0.69 ^{a} ±0.15	1.04 ^{a} ±0.18	0.80 ^{a} ±0.15
ZT planting with 60 × 15 cm crop geometry and 9 t ha^{-1} PSM	16.82 ^{bc} ±1.13	15.37 ^{d} ±1.99	17.26 ^{e} ±0.53	0.84 ^{a} ±0.29	0.78 ^{bc} ±0.08	0.69 ^{ab} ±0.24
ZT planting with 60 × 15 cm crop geometry and 12 t ha^{-1} PSM	18.59 ^{b} ±2.54	18.94 ^{c} ±2.94	22.66 ^{cd} ±1.11	0.65 ^{a} ±0.08	1.02 ^{ab} ±0.08	0.74 ^{a} ±0.21
ZT planting with 60 × 15 cm crop geometry and 15 t ha^{-1} PSM	18.94 ^{b} ±1.21	19.50 ^{c} ±2.48	23.97 ^{bc} ±1.17	0.73 ^{a} ±0.09	1.04 ^{a} ±0.05	0.77 ^{a} ±0.20
SEm±	1.46	1.39	1.07	0.10	0.08	0.08
$LSD_{0.05}$	3.06	2.93	2.25	0.21	0.16	0.16

Data with the same letter in a column are not significantly different. ± indicates SD values.

Table 5. Yield of mustard and succeeding green gram crop under different tillage, crop geometry, and residue amounts during Rabi 2020–2021, 2021–2022 and 2022–2023.

Treatments for Mustard Cultivation	**Seed Yield (t ha^{-1}) of Mustard**			**Seed Yield (t ha^{-1}) of Green Gram**		
	2020–2021	**2021–2022**	**2022–2023**	**2020–2021**	**2021–2022**	**2022–2023**
Control (conventional tillage for ridge and furrow planting of mustard, no crop residue recycling)	0.56 ^{d} ±0.10	0.69 ^{c} ±0.05	0.95 ^{d} ±0.10	0.31 ^{c} ±0.05	0.35 ^{c} ±0.02	0.32 ^{d} ±0.06
ZT planting of mustard with 20 × 10 cm crop geometry and 2 t ha^{-1} paddy straw mulching (PSM)	0.96 ^{c} ±0.16	1.21 ^{b} ±0.50	1.72 ^{abc} ±0.26	0.39 ^{bc} ±0.02	0.55 ^{b} ±0.17	0.52 ^{abc} ±0.01

Table 5. *Cont.*

Treatments for Mustard Cultivation	Seed Yield (t ha^{-1}) of Mustard			Seed Yield (t ha^{-1}) of Green Gram		
	2020–2021	2021–2022	2022–2023	2020–2021	2021–2022	2022–2023
ZT planting of mustard with 20 × 10 cm crop geometry and 4 t ha^{-1} PSM	1.16 ^{abc} ±0.26	1.42 ^{ab} ±0.11	1.78 ^{abc} ±0.36	0.48 ^{a} ±0.09	0.71 ^{a} ±0.15	0.54 ^{abc} ±0.03
ZT planting of mustard with 20 × 10 cm crop geometry and 6 t ha^{-1} PSM	1.34 ^{a} ±0.12	1.44 ^{ab} ±0.34	1.76 ^{abc} ±0.25	0.45 ^{ab} ±0.07	0.79 ^{a} ±0.23	0.58 ^{a} ±0.07
ZT planting of mustard with 25 × 10 cm crop geometry and 2 t ha^{-1} PSM	1.26 ^{ab} ±0.07	1.33 ^{ab} ±0.04	1.60 ^{bc} ±0.06	0.44 ^{ab} ±0.02	0.58 ^{b} ±0.04	0.48 ^{ab} ±0.01
ZT planting of mustard with 25 × 10 cm crop geometry and 4 t ha^{-1} PSM	1.20 ^{abc} ±0.06	1.43 ^{ab} ±0.30	2.01 ^{a} ±0.19	0.46 ^{ab} ±0.07	0.78 ^{a} ±0.11	0.50 ^{b} ±0.03
ZT planting of mustard with 25 × 10 cm crop geometry and 6 t ha^{-1} PSM	1.22 ^{ab} ±0.08	1.59 ^{a} ±0.28	1.85 ^{ab} ±0.28	0.47 ^{ab} ±0.04	0.80 ^{a} ±0.07	0.61 ^{a} ±0.03
ZT planting of mustard with 30 × 10 cm crop geometry and 2 t ha^{-1} PSM	1.25 ^{ab} ±0.12	1.23 ^{ab} ±0.08	1.44 ^{c} ±0.11	0.41 ^{ab} ±0.05	0.59 ^{b} ±0.07	0.46 ^{c} ±0.02
ZT planting of mustard with 30 × 10 cm crop geometry and 4 t ha^{-1} PSM	1.13 ^{ab} ±0.07	1.27 ^{ab} ±0.38	1.52 ^{bc} ±0.12	0.39 ^{bc} ±0.02	0.80 ^{a} ±0.07	0.49 ^{c} ±0.02
ZT planting of mustard with 30 × 10 cm crop geometry and 6 t ha^{-1} PSM	1.05 ^{bc} ±0.08	1.42 ^{ab} ±0.23	1.55 ^{bc} ±0.12	0.44 ^{ab} ±0.06	0.83 ^{a} ±0.07	0.56 ^{abc} ±0.05
SEm±	0.14	0.16	0.17	0.04	0.09	0.03
$LSD_{0.05}$	0.27	0.33	0.35	0.08	0.18	0.07

Data with the same letter in a column are not significantly different. ± indicates SD values.

Table 6. Yield of garlic and succeeding green gram under different tillage, crop geometry, and residue amount during Rabi 2020–2021 and 2022–2023.

Treatments for Garlic Cultivation	Bulb Yield (t ha^{-1}) of Garlic			Seed Yield (t ha^{-1}) of Green Gram		
	2020–2021	2021–2022	2022–2023	2020–2021	2021–2022	2022–2023
Control (conventional tillage for ridge and furrow planting of garlic, no crop residue recycling)	2.26 ^{d} ±1.42	3.39 ^{d} ±0.48	2.18 ^{e} ±1.12	0.25 ^{c} ±0.003	0.16 ^{d} ±0.02	0.29 ^{b} ±0.02
ZT planting of garlic with 20 × 10 cm crop geometry and 3 t ha^{-1} paddy straw mulching (PSM)	3.53 ^{cd} ±1.36	4.68 ^{c} ±1.37	5.44 ^{cd} ±0.78	0.27 ^{bc} ±0.06	0.19 ^{cd} ±0.02	0.35 ^{ab} ±0.03
ZT planting of garlic with 20 × 10 cm crop geometry and 5 t ha^{-1} PSM	3.98 ^{bc} ±1.49	6.11 ^{b} ±1.35	6.14 ^{bc} ±1.13	0.26 ^{bc} ±0.03	0.22 ^{abc} ±0.02	0.35 ^{ab} ±0.03
ZT planting of garlic with 20 × 10 cm crop geometry and 7 t ha^{-1} PSM	4.09 ^{bc} ±1.15	7.52 ^{a} ±1.84	8.21 ^{a} ±0.99	0.28 ^{bc} ±0.03	0.26 ^{a} ±0.01	0.37 ^{a} ±0.03
ZT planting of garlic with 25 × 10 cm crop geometry and 3 t ha^{-1} PSM	5.05 ^{ab} ±0.55	4.88 ^{c} ±1.77	4.81 ^{d} ±1.00	0.34 ^{ab} ±0.08	0.20 ^{bc} ±0.05	0.31 ^{ab} ±0.04
ZT planting of garlic with 25 × 10 cm crop geometry and 5 t ha^{-1} PSM	5.18 ^{ab} ±1.92	6.46 ^{ab} ±1.24	5.62 ^{cd} ±1.01	0.35 ^{ab} ±0.09	0.24 ^{abc} ±0.01	0.31 ^{ab} ±0.05
ZT planting of garlic with 25 × 10 cm crop geometry and 7 t ha^{-1} PSM	5.38 ^{ab} ±1.98	6.94 ^{ab} ±2.14	5.97 ^{cd} ±1.20	0.41 ^{a} ±0.07	0.23 ^{ab} ±0.005	0.33 ^{ab} ±0.05

Table 6. *Cont.*

Treatments for Garlic Cultivation	Bulb Yield (t ha^{-1}) of Garlic			Seed Yield (t ha^{-1}) of Green Gram		
	2020–2021	2021–2022	2022–2023	2020–2021	2021–2022	2022–2023
ZT planting of garlic with 30 × 10 cm crop geometry and 3 t ha^{-1} PSM	4.79 ^{abc} ±1.33	4.55 ^{c} ±1.62	5.28 ^{cd} ±0.65	0.27 ^{bc} ±0.02	0.17 ^{cd} ±0.06	0.30 ^{b} ±0.02
ZT planting of garlic with 30 × 10 cm crop geometry and 5 t ha^{-1} PSM	5.40 ^{ab} ±2.27	7.06 ^{ab} ±1.34	6.66 ^{bc} ±0.13	0.30 ^{bc} ±0.02	0.25 ^{a} ±0.02	0.33 ^{ab} ±0.04
ZT planting of garlic with 30 × 10 cm crop geometry and 7 t ha^{-1} PSM	6.05 ^{a} ±1.77	7.19 ^{ab} ±2.06	7.57 ^{ab} ±0.88	0.31 ^{bc} ±0.01	0.26 ^{a} ±0.03	0.35 ^{ab} ±0.05
SEm±	0.70	0.54	0.73	0.04	0.03	0.03
$LSD_{0.05}$	1.46	1.13	1.52	0.08	0.05	0.06

Data with the same letter in a column are not significantly different. ± indicates SD values.

3.4.2. Yield and Economics of Cropping Systems

The cropping system performance was evaluated in terms of the rice equivalent yield (REY), cost of cultivation, gross return, net return, and benefit–cost ratio (Tables 7–9). During 2020–2021, the highest REY of 17.63 t ha^{-1} was observed in the rice–zero-tillage planting with paddy straw mulching (ZTPSM) in the potato–ZTPSM in the green gram cropping system. The cost of cultivation was higher in the conventional system of cultivation compared to that with zero tillage and residue management. The highest net return (USD 2092 ha^{-1}) was also observed in the above cropping system, however, the highest system BCR (2.15) was recorded in the rice–ZT-garlic system with paddy straw mulching (Table 7).

Table 7. Rice-equivalent yield and economics of rice-based cropping system in coastal saline region under different conventional and zero tillage and residue management during Rabi 2020–2021.

Rice-Based Cropping Systems	Rice Equivalent Yield (t ha^{-1})	Cost of Cultivation (USD ha^{-1})	Gross Return (USD ha^{-1})	Net Return (USD ha^{-1})	BCR
Rice–fallow *	4.58 ^{g}	708 ^{j}	1170 ^{h}	462 ^{c}	1.65 ^{c}
Rice–potato *	10.78 ^{d}	2082 ^{c}	2735 ^{cd}	653 ^{b}	1.31 ^{d}
Rice–mustard *	5.93 ^{f}	1036 ^{i}	1511 ^{gh}	474 ^{c}	1.46 ^{cd}
Rice–garlic *	9.42 ^{de}	1700 ^{f}	2392 ^{ef}	692 ^{b}	1.41 ^{d}
Rice–potato–green-gram *	12.36 ^{c}	2408 ^{a}	3068 ^{c}	660 ^{bc}	1.27 ^{d}
Rice–mustard–green-gram *	7.12 ^{f}	1362 ^{g}	1812 ^{fg}	450	1.33 ^{d}
Rice–garlic–green-gram *	10.38 ^{de}	2053 ^{c}	2594 ^{de}	541 ^{bc}	1.26 ^{d}
Rice–ZTPSM potato **	15.05 ^{b}	1971 ^{d}	3812 ^{b}	1841 ^{a}	1.93 ^{b}
Rice–ZTPSM-mustard **	6.46 ^{f}	1003 ^{i}	1645 ^{g}	642 ^{bc}	1.64 ^{c}
Rice–ZTPSM-garlic **	14.92 ^{b}	1756 ^{e}	3779 ^{b}	2023 ^{a}	2.15 ^{a}
Rice–ZTPSM-potato–ZTPSM-green-gram **	17.63 ^{a}	2261 ^{b}	4353 ^{a}	2092 ^{a}	1.93 ^{b}
Rice–ZTPSM-mustard–ZTPSM-green-gram **	8.15 ^{e}	1252 ^{h}	2070 ^{f}	818 ^{b}	1.65 ^{c}
Rice–ZTPSM-garlic–ZTPSM-green-gram **	16.12 ^{ab}	2059 ^{c}	4031 ^{a}	1972 ^{a}	1.96 ^{ab}

Table 7. *Cont.*

Rice-Based Cropping Systems	Rice Equivalent Yield (t ha^{-1})	Cost of Cultivation (USD ha^{-1})	Gross Return (USD ha^{-1})	Net Return (USD ha^{-1})	BCR
SEm±	0.75	13	117	117	0.06
$LSD_{0.05}$	2.20	37	342	341	0.19

* Conventional tillage. ** After harvest of Kharif rice, subsequent crops were planted under zero tillage and with retention of previous crop residues (for potato, mustard, and garlic as per treatments and for green gram, all crop residues of previous crop retained). Data with the same letter in a column are not significantly different. ZTPSM: zero-tillage planting with paddy straw mulching.

Table 8. Rice-equivalent yield and economics of rice-based cropping system in coastal saline region under different conventional and zero tillage and residue management during Rabi 2021–2022.

Rice-Based Cropping Systems	Rice Equivalent Yield (t ha^{-1})	Cost of Cultivation (USD ha^{-1})	Gross Return (USD ha^{-1})	Net Return (USD ha^{-1})	BCR
Rice–fallow *	4.94 ^{f}	706 ^{l}	1218 ^{i}	512 ^{fg}	1.73 ^{d}
Rice–potato *	16.10 ^{c}	2611 ^{f}	3337 ^{e}	726 ^{f}	1.28 ^{fg}
Rice–mustard *	7.24 ^{ef}	1104 ^{j}	1655 ^{h}	551 ^{fg}	1.50 ^{e}
Rice–garlic *	15.11 ^{cd}	2632 ^{e}	3149 ^{e}	517 ^{fg}	1.20 ^{gh}
Rice–potato–green-gram *	17.78 ^{c}	2944 ^{b}	3656 ^{d}	712 ^{f}	1.24 ^{g}
Rice–mustard–green-gram *	8.87 ^{e}	1437 ^{h}	1965 ^{g}	528 ^{fg}	1.37 ^{f}
Rice–garlic–green-gram *	15.86 ^{c}	2965 ^{a}	3291 ^{e}	326 ^{g}	1.11 ^{h}
Rice–ZTPSM-potato **	25.84 ^{b}	2513 ^{g}	5186 ^{b}	2673 ^{b}	2.06 ^{a}
Rice–ZTPSM-mustard **	9.51 ^{e}	1096 ^{k}	2086 ^{g}	990 ^{e}	1.90 ^{bc}
Rice–ZTPSM-garlic **	23.42 ^{b}	2612 ^{f}	4724 ^{c}	2112 ^{c}	1.81 ^{c}
Rice–ZTPSM-potato–ZT-green-gram **	29.90 ^{a}	2845 ^{d}	5951 ^{a}	3106 ^{a}	2.09 ^{a}
Rice–ZTPSM-mustard–ZT-green-gram **	12.82 ^{d}	1419 ^{i}	2719 ^{f}	1299 ^{d}	1.92 ^{b}
Rice–ZTPSM-garlic–ZT-green-gram **	24.45 ^{b}	2935 ^{c}	4923 ^{c}	1987 ^{c}	1.68 ^{d}
SEm±	1.02	2	81	79	0.03
$LSD_{0.05}$	2.98	6	237	231	0.09

* Conventional tillage. ** After harvest of Kharif rice, subsequent crops were planted under zero tillage and with retention of previous crop residues (for potato, mustard, and garlic as per treatments and for green gram, all crop residues of previous crop retained). Data with the same letter in a column are not significantly different.

Table 9. Rice-equivalent yield and economics of rice-based cropping system in coastal saline region under different conventional and zero tillage and residue management during Rabi 2022–2023.

Rice Based Cropping Systems	Rice Equivalent Yield (t ha^{-1})	Cost of Cultivation (USD ha^{-1})	Gross Return (USD ha^{-1})	Net Return (USD ha^{-1})	BCR
Rice–fallow	2.99 ^{f}	705 ^{g}	1091 ^{l}	385 ^{h}	1.55 ^{g}
Rice–potato	11.52 ^{d}	2545 ^{c}	3248 ^{f}	703 ^{f}	1.28 ^{i}
Rice–mustard	5.25 ^{f}	1087 ^{f}	1663 ^{k}	576 ^{g}	1.53 ^{g}
Rice–garlic	8.18 ^{e}	2540 ^{c}	2404 ^{h}	−136 ^{i}	0.95 ^{k}
Rice–potato–green-gram	12.66 ^{d}	2863 ^{a}	3537 ^{e}	674 ^{f}	1.24 ^{j}

Table 9. *Cont.*

Rice Based Cropping Systems	Rice Equivalent Yield (t ha^{-1})	Cost of Cultivation (USD ha^{-1})	Gross Return (USD ha^{-1})	Net Return (USD ha^{-1})	BCR
Rice–mustard–green-gram	6.39 ^{f}	1406	1952 ^{j}	546 ^{g}	1.39 ^{h}
Rice–garlic–green-gram	9.22 ^{e}	2858 ^{a}	2666 ^{g}	−192 ^{i}	0.93 ^{k}
Rice–ZTPSM-potato *	22.22 ^{b}	2446 ^{d}	5560 ^{b}	3114 ^{b}	2.27 ^{a}
Rice–ZTPSM-mustard *	8.09 ^{e}	1079 ^{f}	2110 ^{i}	1031 ^{e}	1.96 ^{c}
Rice–ZTPSM-garlic *	19.20 ^{c}	2521 ^{c}	4819 ^{d}	2298 ^{c}	1.91 ^{d}
Rice–ZTPSM-potato–ZT-green-gram *	24.65 ^{a}	2763 ^{b}	6170 ^{a}	3407 ^{a}	2.23 ^{b}
Rice–ZTPSM-mustard–ZT-green-gram *	9.99 ^{e}	1389 ^{e}	2586 ^{g}	1198 ^{d}	1.86 ^{e}
Rice–ZTPSM-garlic–ZT-green-gram *	20.38 ^{bc}	2830 ^{a}	5120 ^{c}	2290 ^{c}	1.81 ^{f}
SEm±	0.78	19	38	19	0.01
$LSD_{0.05}$	2.27	56	112	56	0.02

* After harvest of Kharif rice, subsequent crops were planted under zero tillage and with retention of previous crop residues (for potato, mustard, and garlic as per treatments and for green gram, all crop residues of previous crop retained). Data with the same letter in a column are not significantly different.

During 2021–2022, the highest REY of 29.90 t ha^{-1} was observed in the rice–ZT-potato–ZT-green-gram cropping system involving paddy straw mulching. The highest net return (USD 3106 ha^{-1}) and BCR (2.09) were also observed in the above cropping system (Table 8).

During 2022–2023, the highest REY of 24.65 t ha^{-1} was observed in the rice–ZT-potato–ZT-green-gram cropping system involving paddy straw mulching. The highest net return (USD 3407 ha^{-1}) was also observed in the above cropping system, however, the BCR was more than 2.0 for the rice–ZTPSM-potato and rice–ZTPSM-potato–ZT-green-gram cropping systems (Table 9). Cropping system intensification in rice-based systems following conventional practices and by growing garlic after rice resulted in a negative net return, with a BCR less than unit, indicating uneconomical investment.

3.5. Water Footprint

The water footprint of the cropping systems was significantly (p < 0.001) reduced with the adoption of conservation agricultural practices (Figure 5). The mean water footprints of the six cropping systems (rice–potato, rice–mustard, rice–garlic, rice–potato–green-gram, rice–mustard–green-gram, and rice–garlic–green-gram) under conventional and conservation agriculture were 1489 and 856 m^{3} t^{-1} rice eq. yield, respectively. The rice–ZT-potato with paddy straw mulching had the lowest irrigation water footprint (589 m^{3} t^{-1}), followed by rice–ZT-potato with paddy straw mulching–ZT green gram system (595 m^{3} t^{-1} rice-eq. yield).

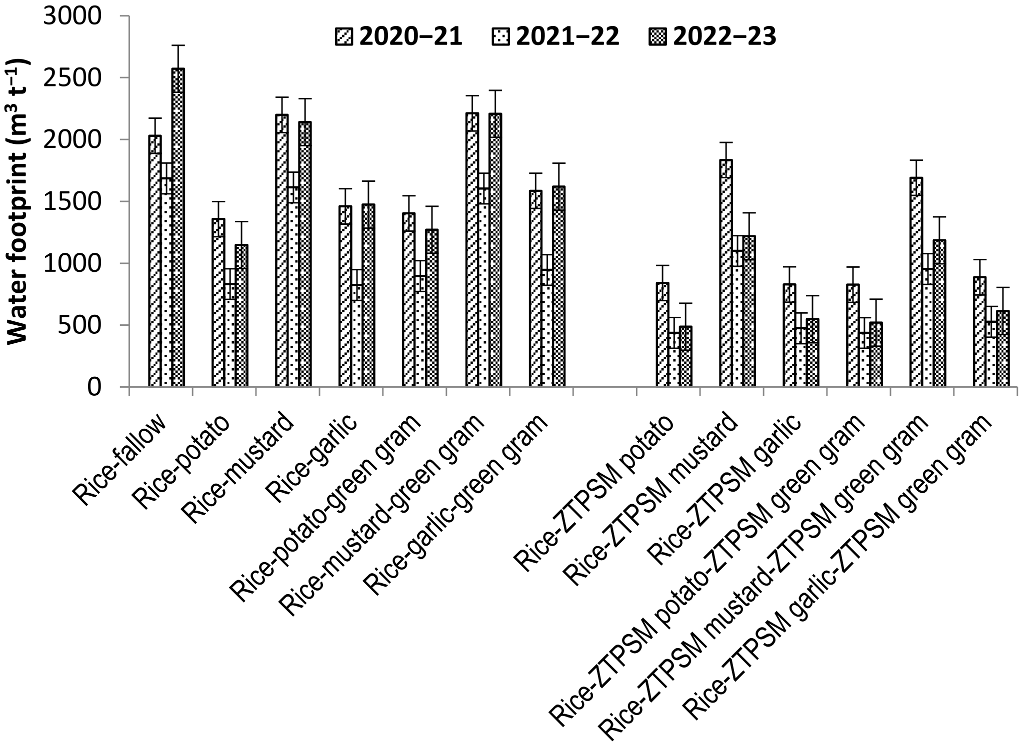

Figure 5. The water footprint of rice-based cropping systems under conventional and conservation agricultural practices. Vertical lines in a bar show the standard error of means.

4. Discussion

Crop residue recycling, particularly using paddy straw as a mulch (PSM), in the subsequent Rabi crops had several positive impacts on the soil, as well as on the crop yield and quality. In this study, we observed positive effects of PSM such as reducing the soil salinity, suppressing weeds, increasing the soil organic carbon, reducing the water footprint, and increasing the crop yield and economics. Straw mulch significantly enhanced the water use efficiency (WUE) by reducing soil moisture losses and, therefore, effectively improving the plant available water [36]. A significantly higher WUE was observed under rice straw mulch (4.99 kg m^{-3}) compared to non-mulch (4.16 kg m^{-3}) treatment in the case of squash (*Cucurbita pepo* L.) in a saline soil (ECe 12.6 dS m^{-1}) in southwest Cairo, Egypt [37]. The rice straw mulch significantly increased the soil water content by 3–9%, decreased the soil penetration resistance by 28–77%, and the crack volume by 84–91% at the upper soil layer (0–30 cm) relative to the no-mulch treatment [38].

Sustainable cropping system intensification in coastal salt-affected regions is possible through a rice–ZT-potato–ZT-green-gram system with paddy straw recycling during the Rabi season, as evidenced by its lower cultivation cost, higher net return (Tables 7–9), and lower water footprint (Figure 5). The mean cost of cultivation (average of three years) of the rice–potato–green-gram system reduced from USD 2738 ha^{-1} under conventional practices to USD 2623 ha^{-1} with the adoption of conservation practices. During the three years of study, the highest net return (USD 2092, 3106, and 3407 ha^{-1} in 2020–2021, 2021–2022, and 2022–2023, respectively) was observed for this cropping system. Conservation-agriculture-based residue retained integrated crop management in maize–wheat rotation, reduced the cost of production by 9.54%, gave 24.3–27.4% additional returns, and the sustainable yield index was 13.4–18.6% greater compared to conventional business-as-usual practices [39].

Residue retention has the largest positive impact on conservation agriculture productivity compared to other management practices and has a more than 50% chance of outperforming conventional tillage systems. Conservation-agriculture-based residue recycling is a sustainable agricultural practice across geographical and climatological regions [40]. Successful weed management is one of the critical issues for the sustainability of conservation agriculture [41]. All the three components of conservation agriculture (minimum tillage, permanent soil cover, and crop diversification) reduce weed populations under medium- to long-term practice [42]. For the promotion of conservation agriculture technologies, there should be appropriate machines, the provision of alternates to crop residues for livestock feeding, the upgrading of skills and scientific manpower, and overcoming the bias or mindset about tillage [43]. The selection of suitable crops for rotation in the system is another important aspect of the success of conservation agriculture. In our study, green gram was found to be a suitable cover crop in rotation with potato and mustard, however, after garlic, the cultivation of green gram crop did not significantly increase the system net return. However, the soil building effect of the inclusion of legume crops on increasing the soil organic carbon and total nitrogen is one of the most important aspects of sustainability [44]. For the wider adoption of conservation agriculture, the longer-term gains and public effects of the technology should be emphasized, rather than shorter-term private costs and benefits [45].

5. Conclusions

Soil salinity in the coastal region during the post monsoon seasons can be managed by the surface retention of previous rice crop straw as mulch on the soil surface. The higher the amount of paddy straw cover on the soil surface, the lesser the salinity build-up. A combination of the zero-tillage planting of Rabi season crops with paddy straw mulching with crop rotations resulted in higher crop yields and system profitability. These conservation agricultural practices had a better impact on soil by improving the soil organic carbon status, suppressing weed menace, and reducing the water footprint. The cropping system intensification involving rice, the zero-tillage planting of potato, and the zero-tillage planting of green gram is recommended as a sustainable option for coastal regions affected by waterlogging during the monsoon season and soil salinity and irrigation water scarcity during the post-monsoon period. The results of this study have relevance for the salt-affected region of the Ganges Delta and could be up-scaled in other regions with similar agro-climatic conditions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/soilsystems8030080/s1, Table S1: Analysis of variance (ANOVA) of various parameters.

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