land

MDPI

Article

Potato Cultivation Under Zero Tillage and Straw Mulching: Option for Land and Cropping System Intensification for Indian Sundarbans

Saikat Dey [1,†], Sukamal Sarkar [1,†], Anannya Dhar [1], Koushik Brahmachari [2,†], Argha Ghosh [3], Rupak Goswami [4] and Mohammed Mainuddin [5,*]

1 Division of Agronomy, School of Agriculture and Rural Development, Ramakrishna Mission Vivekananda Educational and Research Institute, Narendrapur, Kolkata 700103, West Bengal, India; saikatdey5538@gmail.com (S.D.); sukamal.sarkar@gm.rkmvu.ac.in (S.S.); anannyaquizzerdhar@gmail.com (A.D.)
2 Department of Agronomy, Faculty of Agriculture, Bidhan Chandra Krishi Viswa Vidyalaya, Mohanpur, Nadia 741252, West Bengal, India; brahmacharibckv@gmail.com
3 Department of Agricultural Meteorology, Odisha University of Agriculture and Technology, Bhubaneswar 751003, Odisha, India; ghoshargha4@gmail.com
4 Division of Agriculture and Rural Development, School of Agriculture and Rural Development, Ramakrishna Mission Vivekananda Educational and Research Institute, Narendrapur, Kolkata 700103, West Bengal, India; rupak.goswami@gm.rkmvu.ac.in
5 CSIRO Environment, Canberra 2601, Australia
* Correspondence: mohammed.mainuddin@csiro.au
† These authors contributed equally to this work.

Abstract: Agriculture in the Indian Sundarbans deltaic region primarily depends on a rice-based monocropping system during the rainy season, with the subsequent season often remaining fallow. To mitigate this issue, a series of experiments using zero tillage and straw mulching (ZTSM) potato cultivation were conducted over eight consecutive years (2017–2024) across various islands in the Sundarbans Delta, West Bengal, aimed to intensify the cropping system and ensure the betterment of the land use pattern using climate-smart agricultural practices. In the initial two years, the experiments concentrated on assessing different potato cultivars and nutrient dosages under zero tillage and paddy straw mulching conditions. During the subsequent years, the focus shifted to field demonstrations under diverse climatic conditions. The research included the application of different macronutrients and growth regulators, in combination with different depths of straw mulching. In the final years of the study, the intervention was dedicated solely to the horizontal expansion of cultivated land. These initiatives aimed to enhance agricultural productivity and sustainable land use in the polders, promoting climate-resilient farming practices. From the sets of experiments, we standardized the sustainable nutrient management strategies and selection of appropriate potato cultivars vis-à-vis depth of straw mulching and, finally, the overall best agronomic practices for the region. The adoption of the ZTSM potato cultivation system demonstrated considerable success, as evidenced by the remarkable increase in the number of farmers employing this sustainable agricultural practice. The number of farmers practicing zero tillage potato cultivation surged from 23 in the initial year to over 1100, covering an area of more than 15 ha, highlighting the effectiveness of the technology. The analysis of the estimated adoption also showed that more than 90% adoption is likely to be achieved within a decade. This potential expansion underscores the benefits of the ZTSM potato cultivation system in improving soil health, conserving water, and reducing labour and costs. As more farmers recognize the advantages of zero tillage potato mulching, this approach is poised to play a pivotal role in sustainable agriculture, enhancing productivity while promoting environmental stewardship.

Academic Editors: Ognjen Žurovec, Nani Raut and Sabrija Čadro

Received: 15 January 2025
Revised: 21 February 2025
Accepted: 4 March 2025
Published: 7 March 2025

Citation: Dey, S.; Sarkar, S.; Dhar, A.; Brahmachari, K.; Ghosh, A.; Goswami, R.; Mainuddin, M. Potato Cultivation Under Zero Tillage and Straw Mulching: Option for Land and Cropping System Intensification for Indian Sundarbans. *Land* **2025**, *14*, 563. https://doi.org/10.3390/land14030563

Keywords: conservation agriculture; sustainability; potato; reduced tillage; tuber quality; coastal saline zone

1. Introduction

Crop production with traditional technologies often complicates the securing of optimal yields and the provision of food, nutritional, and economic security to climatologically vulnerable areas of the coastal saline zones of the Indian subcontinent. India is surrounded by a long coastline of 8129 km, and the Coastal Saline Zone (CSZ) in West Bengal spreads over an area of 14 lakh hectares, covering 78 blocks across six southern districts [1]. Despite having greater biodiversity and ample amounts of natural resources, which are significant for farming and allied activities [2,3], the productivity of these divisions is lower than the national average due to several constraints associated with the soil–water–climate [4–6]. Agricultural activities in this region remain underexploited due to several factors, while the impacts of climate change, such as recurrent cyclones, prolonged dry spells, and seawater intrusion are some of the major factors making the deltaic ecosystems' climate vulnerable and unproductive [7]. Therefore, the livelihood of the people in this region suffers from lower agricultural productivity due to the threat of global warming and climate change [8].

The coastal saline zones of West Bengal, Sundarbans uninterruptedly face a range of limitations that may create a barrier to intensifying the cropping systems through the addition of one more crop in the dry *Rabi* season (winter), as well as in the pre-*Kharif* season (summer). Many scientists have anticipated that coastal zones will emerge as the most vulnerable regions in the future, primarily due to flooding and the invasion of seawater into farmland [9], resulting in the scarcity of freshwater during dry seasons, coupled with the dynamicity of soil salinity across both surface and subsurface layers [10,11], deteriorating the soil quality and making the soil unproductive for subsequent cultivation. Apart from the homestead upland, the crop fields of this region are often classified as medium-up, medium-low, and lowlands, among which the latter two are usually inundated by floods and rainwater, associated with poor drainage [12]. Except for the extremely saline island situation, in the coastal zone of West Bengal, the climatic conditions favour intensive cropping. It is possible to take two crops in a year under rainfed conditions and three crops per year under irrigated conditions. In most cases, the farmers of the coastal zone are habituated to following traditional cropping systems, satisfying their own needs, without considering the systems' cost-effectiveness, agroecological suitability, and sustainability [13]. During the winter season, lands mainly remain fallow due to delays in the harvesting of transplanted rainy-season rice and the wetness of the soil. The lands become free, and soils reach working conditions from the end of November to the first week of January, which is not the optimal time for sowing many winter crops. Considering the above context, it is quite certain that it is an urgent necessity to reach the farming community of the Indian Sundarbans with gender-neutral technologies to overcome the present constraints.

The potato (*Solanum tuberosum* L.) is one of the most important crops grown in the world's subtropical and temperate regions. Potatoes are among the staple foods that play a major role in dietary intake, contributing especially to the energy and nutritional needs of the global community. Potatoes are consumed in higher quantities as compared to any other vegetables.

Potatoes possess distinct characteristics due to their neutral flavor, making them highly versatile for culinary applications and compatible with a wide range of food preparations and processing methods. Nevertheless, potatoes can be determined as nutrient-rich food in terms of their high calorific value, fats, and carbohydrates. The potato serves as an affordable source of many other bioactive compounds with health benefits, including ascorbic acid, niacin (vitamin B3), pyridoxine (vitamin B6), dietary fiber, total phenolics, high-quality protein, potassium, and phosphorus.

Next to cereals like rice, wheat, and maize, potato is the only crop that can supplement the need for the food of the country. India now ranks second, next to China, in potato production (45.3 million tonnes) in the world, with an average yield of 22.8 t/ha [14]. India will need to produce approximately 124.88 million tonnes of potatoes by the year 2050, from the current production status (2018–2019) of 53.03 million tonnes, to meet the food demands of its expanding population [15]. Potato production is highly confined to the Gangetic plains of India, and the major contributing states are Uttar Pradesh (32.4%), West Bengal (26.9%), and Bihar (14.6%) [16]. Potato cultivation demands a relatively high level of soil nutrients to provide higher yield and productivity [17]. The high rate of dry matter production results in large amounts of nutrients removed per unit of time, which, generally, most soils cannot supply [18]. Therefore, to optimize potato yield and enhance soil health, the incorporation of organic manures is essential in the nutrient management strategy for potato cultivation. According to Meena et al. [19], the use of organic manures not only reduces the overall cost of cultivation but also improves soil quality and increases crop yield and productivity.

However, 9.6 million hectares of land in eastern India are utilized exclusively during the rainy season, compelling farmers to leave their land fallow during the dry *Rabi* season [20]. This is primarily due to salinity and soil moisture stress, which cause challenges such as excess moisture after rice harvest and deficits during the sowing and growth stages. These factors hinder the timely sowing of subsequent *Rabi* crops and result in poor returns from these ecosystems. Moreover, conventional potato cultivation is hindered due not only to the saline soil, but also to the lack of sweet water and terminal heat stress. Keeping this in mind, the integration of forms of conservation agriculture like zero tillage [21] and mulching [11] could be cost-effective, environment-friendly, and viable agronomic practices adapted globally to increase water use efficiency, reduce soil salinity, ensure soil moisture conservation, and augment crop productivity [22]. In this method, rice stubbles can be efficiently managed, which generally creates many problems in growing the next crop, and farmers often opt for stubble burning, resulting in air pollution and loss of organic matter [23]. Zero tillage enables the early establishment of *Rabi* crops into moist soil soon after rice harvest [11] while improving soil health with the enrichment of soil organic matter, accelerating soil physicochemical and biological activity, and reducing soil compaction and greenhouse gas emissions [24]. Thick mulch helps to retain enough moisture in the soil [25]. Potato cultivation under zero tillage along with the addition of organic mulch is quite a novel and promising technology for stress areas, which not only reduces the cost of cultivation but also helps potato crops to withstand salinity and late-season moisture stress conditions. Therefore, the present study focuses on the following objectives:

(i) The selection of a potato variety suitable for zero-tillage systems of management (ZTSM).
(ii) The optimization of foliar nutrient management for enhancing the performance of potatoes grown in the ZTSM system.
(iii) The efficacy of the application of various biostimulants on the growth, yield, and tuber quality of potatoes grown under the ZTSM system.
(iv) The estimation of the potential adoption of the ZTSM method among the farming community of the Indian Sundarbans delta.

2. Materials and Methods

2.1. Origin of the Technologies

The traditional practice of potato cultivation using paddy straw mulching has been long established and remains prevalent in this region [25]. The working mechanism of the ZTSM potato production system is depicted in Figure 1. However, recent evaluations have sought to standardize this method by identifying suitable potato varieties, optimizing nutrient management, and determining the appropriate mulch thickness. These refinements aim to enhance yield and productivity while maintaining sustainability. The coastal saline zones of West Bengal, especially the Sundarbans islands, have been extremely vulnerable to climatic hazards since time immemorial. Repeated disasters in the last two decades, including multiple cyclones, increased crop field inundation, a significant increase in soil salinity, and constrained irrigation in dry months have destabilized traditional cropping systems in the area and forced a substantial proportion of residents to migrate [25]. The sustainable intensification of such lands requires adopting an enhanced package of agronomic practices that optimize soil moisture retention, promote early crop establishment, and ensure economic viability. The Australian Centre for International Agricultural Research (ACIAR)-funded project, "Cropping System Intensification in the Salt Affected Coastal Zones of Bangladesh and West Bengal, India (CSI4CZ)" (https://www.aciar.gov.au/project/lwr-2014-073, accessed on 5 March 2024), was started in 2016 in the Gosaba islands with a range of interventions, such as experimentation and demonstration of appropriate technology, weather forecasting, salinity mapping, and crop modeling amongst others. One of the important objectives of the project was to develop climate-resilient cropping systems, such as medium-duration *Kharif* rice followed by ZTSM potato cultivation and then summer moong bean [26]. In 2021, the project was extended for a second phase (https://www.aciar.gov.au/project/wac-2020-126, accessed on 6 March 2024) for upscaling the project benefits in adjacent islands, and in 2022, another project, "Indo-Pacific Climate-Smart Agriculture Initiative: Project B: Ganges coastal zone climate-smart agricultural production", was introduced on two more islands to examine the effects of recommended cropping practices identified by the CSI4CZ project. Under these projects, with co-participation from local farmers, we started to standardize the package and practices of ZTSM potato cultivation through series of field experiments.

2.2. Description of the Experimental Area

The experimental area is located in the coastal saline belt of Sundarbans, West Bengal, India, measuring 4, 266 km^2, extending over two districts, with 13 blocks in South 24 Parganas and 6 blocks in North 24 Parganas [27]. The field experiments were conducted for eight years (2017–2018 to 2022–2024) on various farmers' fields on three islands of Indian Coastal Sundarbans, Rangabelia, Satjelia, and Choto Mollakhali (Site-I, Site-II, and Site-III respectively), situated in the district of South 24 Parganas, West Bengal, which lies at an elevation of 2 m above mean sea level. These areas are characterized by long tidal streams, resulting in elevated salinity levels in both water and soil. The soil of the experimental areas was recorded as being heavy in nature, with about 45.2% clay, 28.0% silt, and 26.8% sand, organic carbon of 0.50% (low humus content), saturated water content of 0.42%, and bulk density of 1.53 g cm^{-3}, with an EC (soil: water ratio of 1:5) of 0.90 dS m^{-1}, and pH (soil: water ratio of 1:5) of the soil is 6.45 of the surface soil (0–15 cm). Generally, the soil is sandy clay in texture.

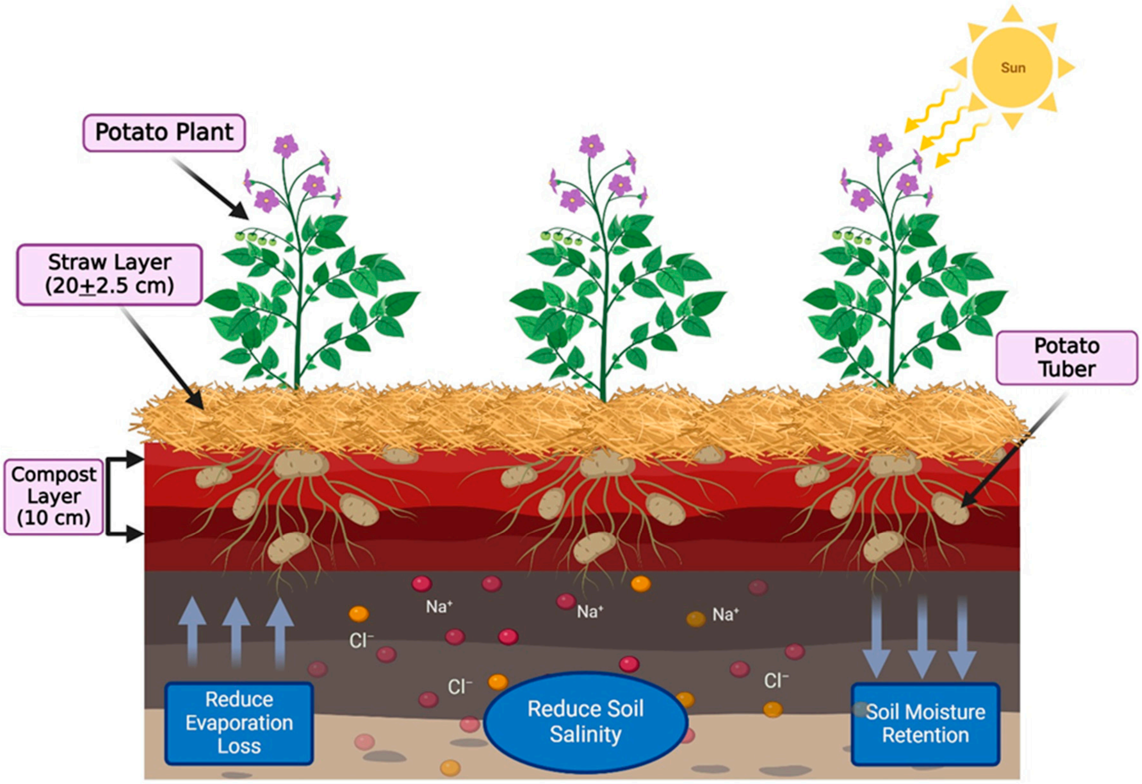

Figure 1. Working principle of zero-tillage potato cultivation with paddy straw mulching (image created with https://BioRender.com; license no: BE27A0036T, accessed on 7 September 2024).

However, in the adjacent river, salinity of the water of these sites can range from 16.8 to 49.9 dS m^{-1}, significantly influencing the ecosystem and soil chemistry [28]. The agroclimatic conditions were generally related to those of the Bay of Bengal, which is very close to these three experimental sites. The average annual rainfall varies between 1377.5 and 2484.5 mm, and it is mostly confined to June to September. The distribution and intensity of the rainfall are likely to be high in July and, to some extent, August. A small amount of rainfall occurs in October and November, which renders the harvesting of the paddy on difficult time and often creates delays in the sowing of succeeding winter crops. Rice is the main crop in this region, and it is mostly cultivated with monsoon rain during the rainy season (June–November), wherein the cool and dry winter (December to February) and summer months (March–April), as well as the dynamics of soil moisture and salinity, compel farmers to leave the land fallow. Therefore, all experiments were conducted during November–December to intensify the fallow rice areas (i.e., after the harvest of the wet season, rice potato experiment was conducted, and the land otherwise remained fallow during the dry season). The various meteorological data during the crop growth period were recorded at the Automatic weather station (EM50 Data Collection System, Decagon Inc., München, Germany), located near the study area, at 22°.1652′ N and 88°.8079′ E.

2.3. Experimental Details

2.3.1. Experimental Design and Treatment Details

Over several years, extensive research has been conducted on potato cultivation under ZTSM technologies, like the selection of suitable potato cultivars, optimizing foliar nutrient management, and assessing the impact of seaweed sap application, to enhance the productivity and quality of potatoes in coastal saline soils. All the research experiments were conducted in randomized complete block design, in which the number of treatments varied according to the experiments. However, the number of replications remained constant, i.e., three. The gross experimental area varied according to the experiments, with a constant net plot size of 20 m^2 (4 m × 5 m). The initial studies were carried out between 2016 and 2017 and focused on comparing the performances of five potato cultivars, namely *Kufri chandramukhi*, *Kufri jyoti*, *S-52*, *S-6*, and a local variety, under both zero tillage and conventional ridge and furrow systems. Following this, in 2018–2019, the research shifted toward optimizing foliar nutrient management for potatoes grown under zero tillage and mulching, with the '*Kufri pukhraj*' variety selected for its short duration (70–80 days), early bulking rate, disease resistance, and suitability for low-input systems [25]. This study involved nine different nutrient treatments tested under similar climatic conditions. The research continued in 2021–2022, with two more innovative experiments. The first examined the impact of various foliar nutrient management practices on potato productivity and quality, using different combinations of di-ammonium phosphate (MOP), muriate of potash (MOP), and triacontanol. The latter experiment investigated the effect of seaweed sap application, particularly *Sargassum* and humic acid, on potato growth and yield. Both studies followed a randomized block design and further refined the approaches to potato cultivation in coastal saline soils. To demonstrate the practical benefits and horizontal expansion of these findings, large-scale field demonstrations were conducted between 2022 and 2024 across three locations, Rangabelia, Choto Mollakhali, and Satjelia Island. These demonstrations, involving 125 farmers in the first year and 100 in the second, effectively showcased the improved techniques for potato cultivation under zero tillage and mulching in the Sundarbans region.

2.3.2. Time of Sowing of Zero Tillage Potato

Since potatoes were cultivated under zero-tillage conditions, there was no need for land preparation. This allows for immediate potato planting after paddy harvesting, even in conditions of higher-than-optimal soil moisture. However, if the field is excessively waterlogged, it should be drained at least two weeks before paddy harvest. In this region, long-duration rice is typically harvested around the first week of December. Nevertheless, introducing medium-duration rice varieties and improved drainage methods could enable earlier harvesting, freeing up fields for subsequent crops.

2.3.3. Land Preparation

Unlike conventional methods, zero-tillage potato cultivation obviates the need for extensive land preparation. Immediately following the monsoon rice harvest, potato tubers were planted without the customary deep ploughing and subsequent ridge formation. Moreover, the synergistic effects of capillary rise of soil salinity and evaporative water losses, exacerbated by moisture deficits in winter and summer, hinder potato cultivation under traditional ridge-and-furrow systems. Consequently, a well-established zero-tillage potato cultivation system incorporating paddy straw mulching emerges as the optimal approach to maximize production in this coastal saline environment [29]. Accordingly, in the case of land preparation, the field must be free from the stagnation of water and to initiate the planting process, a planting line is created using a spade on the wet soil to accommodate the germinated potato tubers.

2.3.4. Selection of Seed Tubers

Seed tubers were carefully selected for purity, health, and uniformity in shape and size. They were either planted whole or cut into 40–50 g pieces. To facilitate early plant growth above the paddy straw, tubers with approximately 1 cm long sprouts were preferred. At the beginning of the study, a multi-cultivar trial was conducted during the 2017–2018 season to identify the most suitable potato variety for the ZTSM potato cultivation technique. Employing a randomized block, five potato cultivars were evaluated: four standard varieties

(*Kufri chandramukhi*, *Kufri jyoti*, *S-52*, and *S-6*) and a locally adapted undescribed cultivar. Potato cultivation was compared under zero-tillage and conventional ridge-and-furrow systems. In subsequent experiments, potato cultivar *Kufri pukhraj* exhibited desirable characteristics for the coastal agroecological conditions. This early maturing (70–90 days) variety is rich in potassium, fiber, and vitamin C. Its tolerance to drought, moderate resistance to late blight, and early bulking properties have contributed to its popularity in India, accounting for 33% of total potato cultivation [30]. The cultivar is also suitable for low-input ecosystems. Therefore, *Kufri Pukhraj* was adopted for subsequent zero-tillage potato cultivation trials.

2.3.5. Seed Treatment

Potato seed treatments are among the important pest management practices used to maximize potato yield and obtain good-quality tuber yield. To avoid the infestation of fungal disease, seed tubers were treated with fungicides, i.e., 0.2% mancozeb in combination with 0.2% carbendazim per kg seed tubers.

2.3.6. Planting of Tubers

Seed tubers that possessed two to three germinating eyes for accelerated germination were selected for planting. These tubers were placed above a layer of locally prepared farmyard compost (10 cm thick). Immediately following planting, the tubers were covered with an additional layer of compost [29], followed by a thick (20 ± 2.5 cm) layer of paddy straw, abundantly available in the local area.

2.3.7. Nutrient Management

The recommended dose of fertilizer for potato cultivation was 100–75–75 kg N-P_2O_5-K_2O ha^{-1}, out of which 75–74.05–73.6 kg N-P_2O_5-K_2O ha^{-1} was applied as basal dose, through 10–26–26 (N-P_2O_5-K_2O), urea, single super phosphate (SSP), and muriate of potash (MOP) [29]. The rest of the RDF_{NPK} was applied as a foliar spray. Nitrogen was applied to all the plots through urea when the plants were 10–15 cm tall. Borax (containing 11.36% B) and chelated Zn EDTA (containing 12% Zn) were used as sources for B and Zn, according to the treatment combinations. As a foliar application, 2% urea, 2% DAP, 2% MOP, 0.1% boron, 0.5% Zn, 0.1%, triacontanol (0.05% EC), *Sargassum* seaweed extract, and humic acid (5%) solution were thoroughly sprayed at 30 and 50 DAP at the time of tuber initiation and tuber developmental stage, according to the treatment combinations, by a manual knapsack sprayer (model: AGM/001, ASPEE Sprayers and Farm Mechanised Equipment, Mumbai, Maharashtra, India) with capacity of 16 L.

2.3.8. Irrigation

One of the significant attributes of the zero-tillage potato is its ability to conserve moisture against evaporation loss when exposed directly to sunlight. Three light-life-saving irrigations were given in this method. The first irrigation was given two weeks after planting tubers, at the time of the establishment of seed tubers. The second irrigation was given five weeks after planting, in the third conjugation with the stolon's initiation stage, and the last irrigation was given at the tuber formation stage. However, in this region, during *Rabi*, there was occasional rain, so the irrigation scheduling was adjusted depending on the local rainfall events.

2.3.9. De-Haulming and Harvesting

Haulms (the above-ground portions of the plant) were cut by sickle after the crop attained maturity. Harvesting was performed 75–80 days after planting through simple removal of the paddy straw. As a result of this, the cost of cultivation was lower, and the tubers were not damaged by sudden heavy rain. Lifting of potato tubers was performed manually.

2.4. Crop Measurements

2.4.1. Biometrical Measurements and Estimation of Yield

In each plot, second rows on either side were marked for destructive sampling and for recording other crop growth observations. The middle two rows were marked for the determination of yield. Five plants from each plot were randomly selected and tagged for recording plant height, number of compound leaves per plant^{-1}, and leaf area index at 30, 40, and 70 days after planting. Tuber number per hectare ($\times 10^5$) and tuber yield (t/ha) were estimated after harvesting of the potato tubers. To determine the tuber yield and number, five rows 4 m in length in the center of each treatment plot were taken and finally represented in t/ha.

2.4.2. Quality Parameters of Potato Tubers

After the harvesting of potato tubers, biochemical tests were performed to judge the quality parameters. Total soluble solids (TSSs) were assessed using a digital refractometer based on total refraction, with cloth-strained juice expressed in °Brix. Total titratable acidity was determined through a volumetric procedure, in which a known volume of filtered and diluted juice was titrated against standard NaOH (N/10) using phenolphthalein as an indicator, and the results were expressed as percentage acidity in terms of citric acid [31]. Ascorbic acid content was estimated using the 2,6-dichlorophenol indophenol dye titration method [32]. Specific gravity was measured with the hydrometer method using 3.63 kg of tubers per sample [33]. Tuber hardness was determined using a screw-type penetrometer (Model FT-327, Facchini, Milan, Italy), with the results expressed in kg/cm^2. The pH of the homogenized juice was measured using a pH meter (Acorn pH 6 Meter, Oakton Instruments, Vernon Hills, IL, USA). The specific gravity of potato tubers was measured following water displacement, using the method described by Westermann et al. [34].

2.5. Analysis of Soil Samples

Pre-sowing and post-harvest soil samples from the potato field were collected from the experimental land and processed before analysis. Particle-size distribution of the soils was obtained by following the Hydrometer method [35]. Textural classes of the soils were determined from the percentage contents of sand, silt, and clay, with the help of the triangular textural diagram [36]. Organic carbon was determined by oxidizing soils with 1 (N) $K_2Cr_2O_7$ in the presence of concentrated H_2SO_4 and titrating back the remaining $K_2Cr_2O_7$ with ferrous ammonium sulphate solution, using diphenylamine indicator, following the wet digestion method of Walkley and Black [37].

Soil moisture was recorded at different soil depths (0–15, 15–30, 30–50, 50–80, and 80–120 cm) at 15-day intervals. Soil samples were collected with the help of a screw auger. Next, the soil was taken into an aluminium moisture box. The weight of each box was taken with an electric balance. Subsequently, the soil samples were dried at 105 °C for 72 h. Volumetric soil moisture was recorded at different soil depths at periodic intervals, as stated by [38]. The electrical conductivity of soil suspensions (soil: water: 1:5) was measured at room temperature (28 °C) by using a direct reading conductivity meter (model: Systronics, 363) [39].

2.6. Preparation of the Location Map

The location data of the potato fields were collected during the field survey and mapped on the NDVI (Normalized Difference Vegetation Index) layer of the corresponding years. The MODIS (Moderate Resolution Imaging Spectroradiometer) NDVI data were collected from the open access cloud computing platform Google Earth Engine (GEE) for the month of February in each year and mapped using the open source QGIS 3.16 (Quantum Geographic Information System) software.

2.7. Estimation of Potential Adoption

The Adoption and Diffusion Outcome Prediction Tool (ADOPT) was used to estimate the adoption potential of ZTSM in the trial and adjacent locations. The underlying framework guiding ADOPT is factor combinations related to the innovation (i.e., ZTSM) and potential adopters vs. learning and relative advantage of the innovation [40]. ADOPT predicts the peak level (percentage) and time to adoption and identifies the most sensitive factors affecting them. Input data for the ADOPT were collected through focus group discussions with ZTSM farmers and other stakeholders associated with the trials and demonstration of the ZTSM technology.

2.8. Statistical Analysis

Statistical assessment was performed by the analysis of variance (ANOVA) for randomized block design (RBD) based on the guidelines given by Gomez and Gomez [41]. The significance of the difference in source of variance was tested by mean squared error by Fisher Snedecor's 'F' test at a probability level of 0.05. For comparison of 'F' values and computation of critical difference (CD) at 5% level of significance, Fisher and Yates' table was consulted. Excel software (version 2018, Microsoft Inc., Redmond, WA, USA) and Origin Pro (2024) were used to draw graphs and figures. The details of each experiment, along with the experimental design used, are given in Supplementary Table S1.

3. Results

3.1. Growth Parameters of Potato

Different potato growth parameters, such as plant height, plant and tuber dry weight, and the number of main branches/plants, were analyzed at different growth stages to compare the performances among the different treatments in various experiments. Significant variations in different growth parameters were observed. Amongst the different potato cultivars, throughout the growth period, the maximum plant heights were recorded for *Kurfi. Jyoti* (42.1 cm, 57.1 cm, and 59.7 cm at 50, 70, and 90 days after sowing), followed by *Kufri chandramukhi* and *S-6*. The lowest plant heights were recorded in local cultivars throughout the growth period (Figure 2a). The maximum number of main branches/plants was recorded from *Kufri chandramukhi*, which was closely followed by *Kufri jyoti* (Figure 2b). On the other hand, the local cultivars produced the minimum main branch/plant throughout the growth period. In harmony with the plant height, the maximum average dry matter accumulation was greater for the improved potato cultivars than for the local cultivars. Amongst different potato cultivars, the hybrid potato cultivar *S-6* produced the maximum plant dry weight, and *S-52* closely followed it, throughout the observation period (Figure 2c,d). However, *Kufri jyoti* was used for the subsequent experiments as a crop cultivar because of its short duration (70–90 days) and higher bulking rate.

The different foliar nutrient application treatments had a significant effect on the plant height, number of compound leaves per plant, LAI, and total biomass of potato cv *Kufri pukhraj* (Figure 3). The highest plant height was achieved due to the application of 2% urea at 30 and 50 days after planting, along with 0.1% boron applied 30 days after planting in the ZTSM potato cultivation. At 50 days after planting, the maximum values for the number of compound leaves/plant (63 compound leaves/plant) observed from the plots received 2% urea at 30 and 50 days after planting and 0.1% boron applied at

30 days after planting. The highest LAI and total dry matter accumulation were also observed in the same treatment.

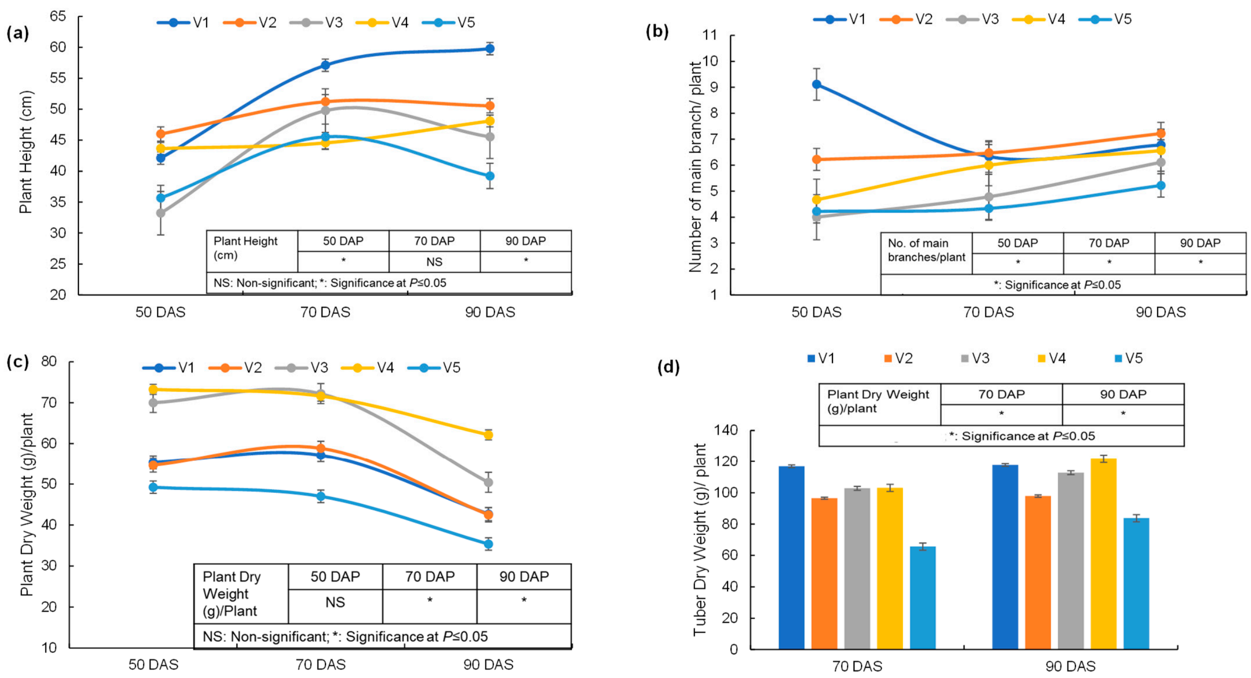

Figure 2. (**a**) Plant height (cm); (**b**) the number of main branches/plants; (**c**) plant dry weight/plant, and (**d**) tuber dry weights/plants of different varieties of potatoes under ZTSM condition (where V1 = *K. chandramukhi*, V2 = *K. jyoti*, V3 = *S-52*, V4 = S6, and V5 = local).

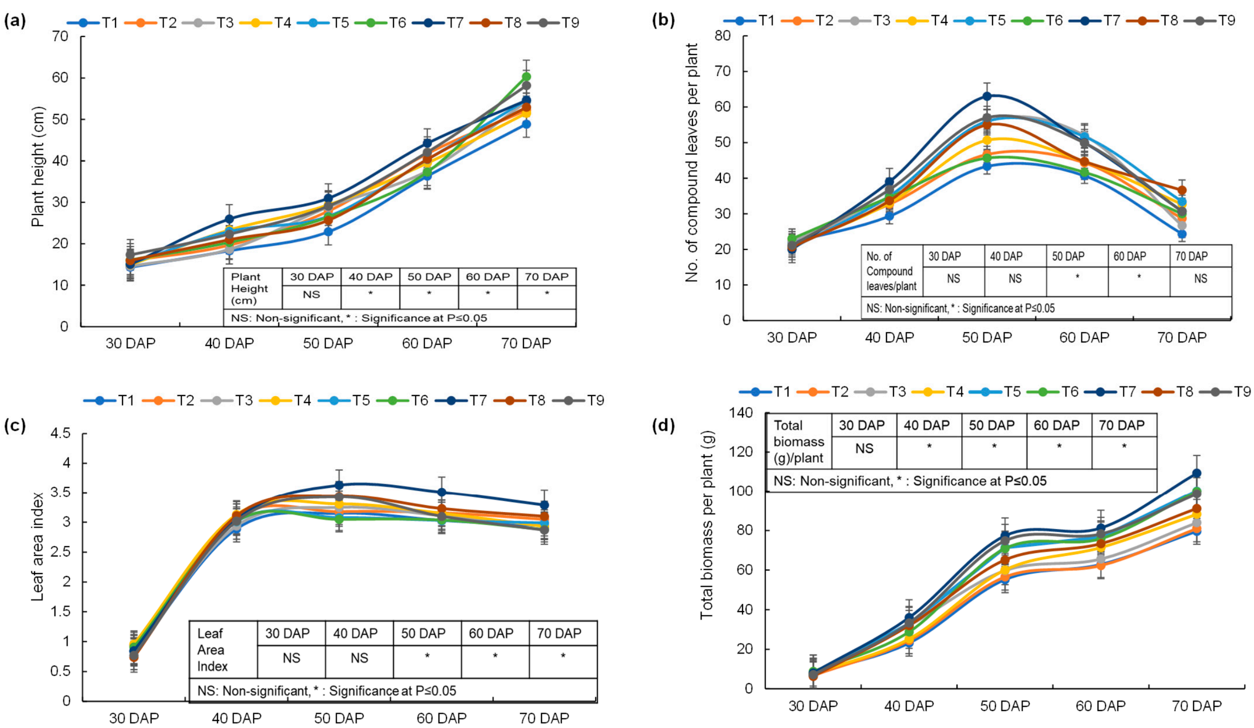

Figure 3. Effect of foliar nutrient management on (**a**) plant height, (**b**) number of compound leaves/plant, (**c**) leaf area index, and (**d**) total biomass per plant of ZTSM system of potato (T1: Control; T2: RDF_{NPK} fb Urea 2% fs $_{30\ DAP}$; T3: RDF_{NPK} fb Urea 2% fs $_{30\ \&\ 50\ DAP}$; T4: RDF_{NPK} fb MOP 2% fs $_{30\ DAP}$; T5: RDF_{NPK} fb Urea 2% fs $_{30\ \&\ 50\ DAP}$ + MOP 2% fs $_{30\ DAP}$; T6: RDF_{NPK} fb Boron 0.1% fs $_{30\ DAP}$; T7: RDF_{NPK} fb Urea 2% fs $_{30\ \&\ 50\ DAP}$ + Boron 0.1% fs $_{30\ DAP}$; T8: RDF_{NPK} fb Zinc 0.5% fs $_{30\ DAP}$; T9: RDF_{NPK} fb Urea 2% fs $_{30\ \&\ 50\ DAP}$ + Zinc 0.5% fs $_{30\ DAP}$).

The biostimulants in the form of seaweed extracts and plant growth regulators were found to have exerted significant effects on the growth parameters of the zero-tillage potato (Figure 4). The plant height of the potato gradually increased as the age of the crop progressed up to 50 days after planting. Thereafter, the rate of growth slightly declined towards maturity (70 days after planting). The highest plant height was recorded with the foliar application of 5% *Sargassum*-based seaweed extract and humic acid at 30 and 50 days after planting. A similar result was observed in the case of the number of compound leaves per plant and leaf area index of potato. The total biomass/plant was seen to increase till the harvest of the crop. The highest values were seen with the foliar application with 5% *Sargassum*-based seaweed extract and humic acid at 30 and 50 days after planting.

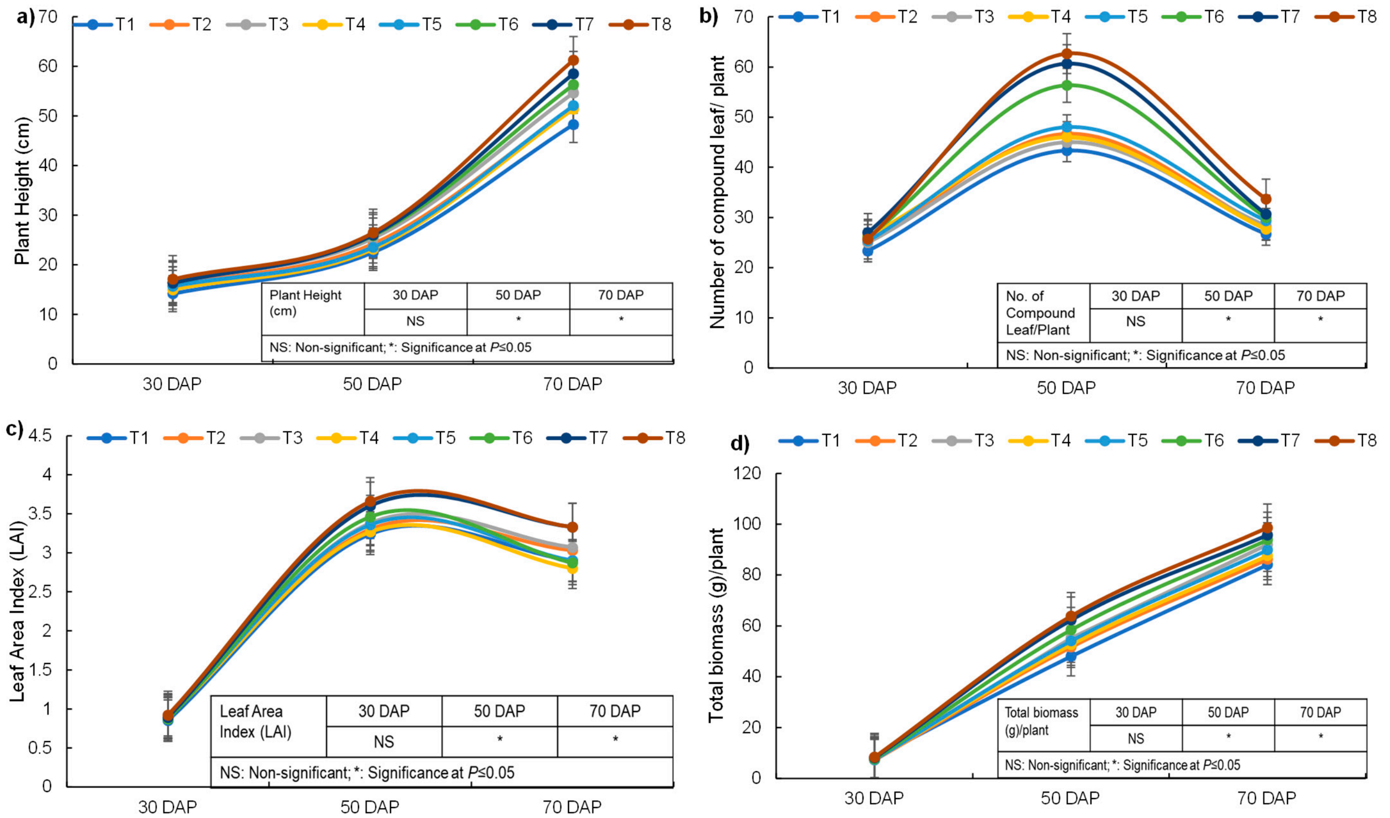

Figure 4. Effects of biostimulants on (**a**) plant height; (**b**) number of compound leaves/plant; (**c**) leaf area index; and (**d**) total biomass/plant of ZTSM potato (where T1: Control, T2: RDF_{NPK} fb *Sargassum* 5% fs $_{30\ DAP}$; T3: RDF_{NPK} fb Sargassum 5% fs $_{30\ DAP\ \&\ 50\ DAP}$; T4: RDF_{NPK} fb Sargassum + humic acid 5% fs $_{30\ DAP}$; T5: RDF_{NPK} fb Sargassum + humic acid 5% fs $_{30\ DAP\ \&\ 50\ DAP}$; T6: RDF_{NPK} fb Triacontanol 0.05% fs $_{30\ DAP}$; T7: RDF_{NPK} fb Triacontanol 0.05% fs $_{30\ DAP\ \&\ 50\ DAP}$; T8: Water).

The application of foliar nutrients and growth regulators affected the growth parameters of the potatoes grown under the zero-tillage system. As the crop became older, the potato plant became taller and grew more compound leaves until it was 60 days after planting. The highest plant height and number of compound leaves were recorded due to the combined application of 2% days after planting, 2% MOP, and 0.1% triacontanol 0.05% EC at 30 and 50 days after planting. The lowest values of the aforementioned parameters were seen in the control. The highest values of the total biomass/plant were also recorded from the treatment mentioned above (Figure 5).

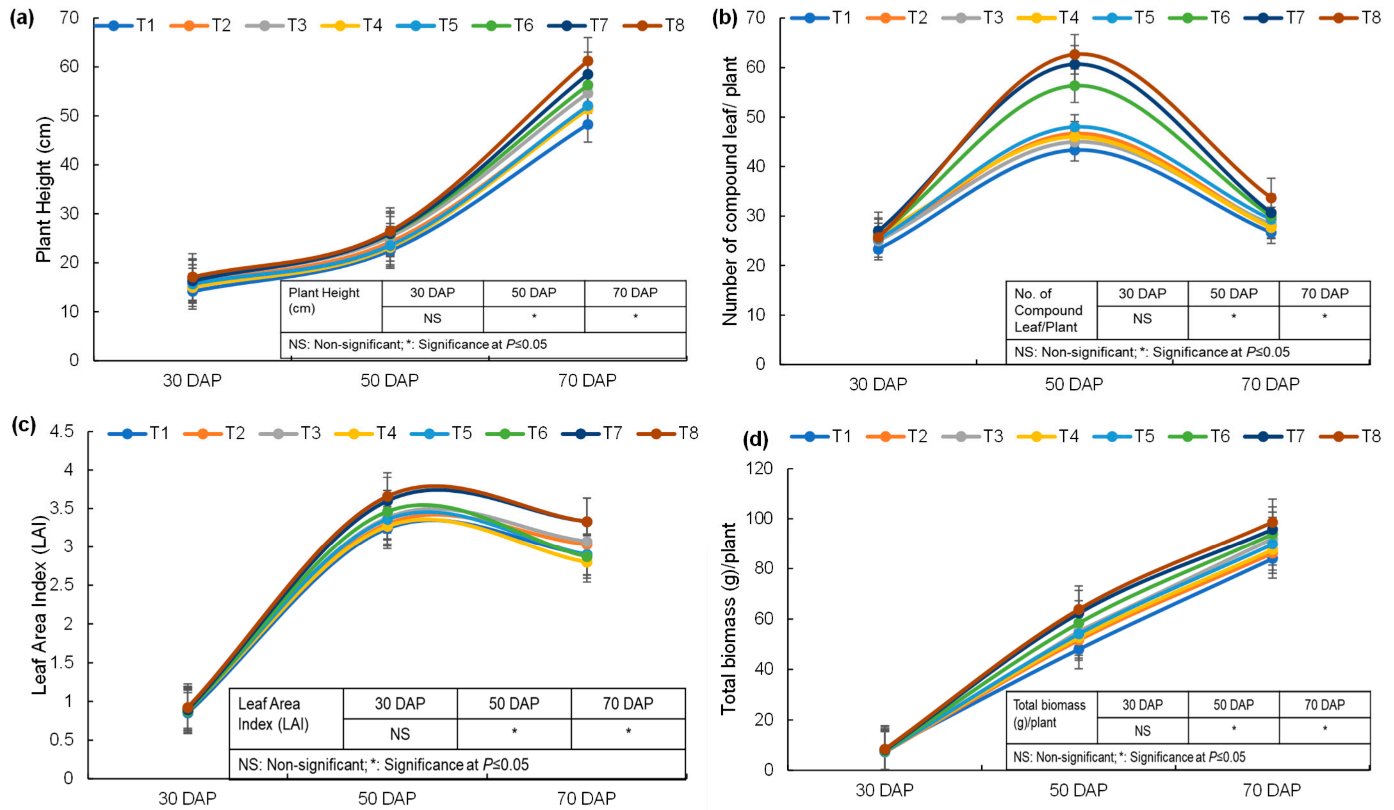

Figure 5. Effects of foliar nutrient and growth regulators on (**a**) plant height; (**b**) the number of compound leaves; (**c**) leaf area index; and (**d**) total biomass/plant (where T1: Water Spray; T2: 2% DAP at 30 DAP; T3: 2% DAP at 30 And 50 DAP; T4: 2% MOP at 30 DAP; T5: 2% MOP at 30 and 50 DAP; T6: 2% DAP and 2% MOP at 30 DAP; T7: 2% DAP and 2% MOP At 30 and 50 DAP; T8: 2% DAP + 2% MOP + 0.1% Triacontanol 0.05% EC (Miraculan) at 30 and 50 DAP).

3.2. Yield Components and Yield of Potatoes

The yield components and yield of the potatoes grown in the zero-tillage mulch system were found to have been influenced significantly by various sets of treatments in different research experiments throughout the period.

The varietal difference had a significant positive effect on the tuber number, as well as the yield of the potatoes (Table 1). The maximum tuber number was recorded for the hybrid potato cultivar, *S-52* (2.30 × 105/ha), which was statistically on par with the rest of the potato cultivars, except the local cultivar (1.65 × 105/ha). For the tuber number, the maximum tuber yield (22.4 t/ha) was obtained from the *S-6* hybrid potato cultivar, which was statistically on par with *Kufri chandramukhi*, *Kufri jyoti*, and a private sector hybrid cultivar, *S-52*.

Table 1. Yield component and yield of different potato cultivars under zero-tillage mulch system.

Potato Cultivars	Tuber Number/ha (×10^5)	Tuber Yield (t/ha)
K. Chandramukhi	2.23 a	19.6 ab
K. Jyoti	2.07 a	19.3 ab
S-52	2.30 a	18.0 ab
S-6	2.29 a	22.4 a
Local	1.65 b	11.9 b

Means followed by different letters are significantly different at $p \leq 0.05$, according to Duncan's multiple range test (DMRT).

The highest value for total tuber/ha was found in the potatoes that were foliar-fertilized with 2% urea at 30 and 50 days after planting and 0.1% boron at 30 days after planting. The foliar application of different macro and micronutrients on the potatoes grown under ZT + M significantly ($p \leq 0.05$) influenced the total tuber yields of the potatoes (*cv. Kufri pukhraj*) (Table 2). The highest tuber yield (26.3 t/ha) was obtained from the plants that received 2% urea at 30 and 50 DAP, along with 0.1% boron at 30 days after planting. The lowest value for the total tuber yield was found in the case of the control, where no nutrients were added.

Table 2. Effects of foliar nutrient management on yield components and yield parameters of zero-tillage mulch potato *cv. Kufri pukhraj*.

Foliar Nutrient Treatments	Tuber Number/ha ($\times 10^5$)	Tuber Yield (t/ha)
Control	2.05	21.3
RDF_{NPK} fb Urea 2% fs $_{30\ DAP}$	2.23	23.3
RDF_{NPK} fb Urea 2% fs $_{30\ \&\ 50\ DAP}$	2.29	24.1
RDF_{NPK} fb MOP 2% fs $_{30\ DAP}$	2.30	22.4
RDF_{NPK} fb Urea 2% fs $_{30\ \&\ 50\ DAP}$ + MOP 2% fs $_{30\ DAP}$	2.39	22.8
RDF_{NPK} fb Boron 0.1% fs $_{30\ DAP}$	2.80	24.5
RDF_{NPK} fb Urea 2% fs $_{30\ \&\ 50\ DAP}$ + Boron 0.1% fs $_{30\ DAP}$	2.92	26.3
RDF_{NPK} fb Zinc 0.5% fs $_{30\ DAP}$	2.27	22.5
RDF_{NPK} fb Urea 2% fs $_{30\ \&\ 50\ DAP}$ + Zinc 0.5% fs $_{30\ DAP}$	2.69	24.1
SEm±	0.14	0.26
CD ($p \leq 0.05$)	0.42	0.79

RDF: recommended dose of fertilizers; fb: followed by; fs: foliar spray; DAP: days after planting.

Biostimulants in the form of seaweed extracts and humic acid were found to have exerted significant effects on the yield of the potatoes. The application of Sargassum-based seaweed extract (5%) along with humic twice, at 30 and 50 days after sowing, resulted in the highest tuber/ha and tuber yield, with a yield advantage of 36.8% over the control, to which no biostimulants were added (Table 3).

Table 3. Effects of biostimulants on yield components and yield parameters of zero-tillage mulch potato *cv. Kufri pukhraj*.

Bio Stimulants Treatments	Tuber Number/ha ($\times 10^5$)	Tuber Yield (t/ha)
Control	4.41	20.1
RDF_{NPK} fb Sargassum 5% fs $_{30\ DAP}$	5.77	24.4
RDF_{NPK} fb Sargassum 5% fs $_{30\ DAP\ \&\ 50\ DAP}$	6.93	24.6
RDF_{NPK} fb Sargassum + humic acid 5% fs $_{30\ DAP}$	6.32	25.1
RDF_{NPK} fb Sargassum + humic acid 5% fs $_{30\ DAP\ \&\ 50\ DAP}$	7.76	27.5
RDF_{NPK} fb Triacontanol (0.05% EC) 0.1% fs $_{30\ DAP}$	5.06	22.3
RDF_{NPK} fb Triacontanol (0.05% EC) 0.1% fs $_{30\ DAP\ \&\ 50\ DAP}$	5.54	23.8
RDF_{NPK} + Water	4.57	21.0
SEm±	0.22	0.52
CD ($p \leq 0.05$)	0.64	1.51

RDF: recommended dose of fertilizers; fb: followed by; fs: foliar spray; DAP: days after planting.

The total number of tubers and the tuber yield of the potatoes varied significantly with the application of different foliar nutrients and growth regulators. The highest values for tuber number per plant (6.67×10^5/ha) and tuber yield/ha (26.2 t/ha) were recorded from the potatoes in which 2% DAP, 2% MOP, and 0.1% triacontanol 0.05% EC at 30 and 50 DAP were foliar-applied (Table 4).

Table 4. Effects of foliar nutrients and growth regulators on yield components and yield parameters of zero-tillage mulch potato *cv. Kufri pukhraj*.

Bio Stimulants Treatments	Tuber Number/ha ($\times 10^5$)	Tuber Yield (t/ha)
Water Spray	5.28	21.6
RDF $_{NPK}$ fb DAP 2% fs $_{30\ DAP}$	5.55	25.1
RDF $_{NPK}$ fb DAP 2% fs $_{30\ \&\ 50\ DAP}$	6.11	25.4
RDF $_{NPK}$ fb MOP 2% fs $_{30\ DAP}$	5.28	24.0
RDF $_{NPK}$ fb MOP 2% fs $_{30\ \&\ 50\ DAP}$	5.55	24.3
RDF $_{NPK}$ fb DAP 2% & MOP 2% fs $_{30\ DAP}$	5.83	25.2
RDF $_{NPK}$ fb DAP 2% & MOP 2% fs $_{30\ and\ 50\ DAP}$	6.39	25.9
RDF $_{NPK}$ fb DAP 2% + MOP 2% & Triacontanol (0.05% EC) 0.1% fs $_{30\ and\ 50\ DAP}$	6.67	26.2
SEm±	0.29	0.30
CD ($p \leq 0.05$)	0.89	0.91

RDF: recommended dose of fertilizers; fb: followed by; fs: foliar spray; DAP: days after planting.

3.3. Quality Parameters of Potatoes

The values for the tuber quality in terms of tuber hardness (kg/cm^2), specific gravity (g/cm^3), TSS (°Brix), juice pH, total acidity of juice (%), and vitamin C content (mg/100 g of fresh weight) were judged to compare among the various sets of treatments.

The application of 2% urea at 30 and 50 days after planting along with 0.1% boron at 30 days after planting resulted in the highest values for tuber hardness (9.50 kg/cm^2), vitamin C content (15.9 mg/100 g of fresh weight), and total soluble solids (5.56 °Brix) in the potatoes, whereas the maximum acidity (2.27) and specific gravity of the tuber (1.08) were recorded due to the application of 0.1% boron at 30 days after planting. The pH value of juice (6.67) nearest to neutral pH was found in the potatoes when 2% urea at 30 and 50 days after planting was applied along with 0.1% boron at 30 days after planting (Figure 6).

The highest values for tuber hardness (9.50 kg/cm^2), specific gravity (1.08 g/cc), Vitamin C (15.2 mg/100 g), and TSS (5.53 °Brix) were recorded for the potatoes receiving *Sargassum*-based seaweed extract (5%) along with humic twice, at 30 and 50 days after sowing. Tubers whose juice pH has a neutral value are good for consumption and storage purposes, and this was found in the potatoes receiving 5% *Sargassum* extract and humic acid at 30 and 50 DAP. The different foliar applications of biostimulants on potatoes grown under ZTSM significantly ($p \leq 0.05$) influenced the acidity (%) of the potato tubers (*cv. Kufri Pukhraj*) (Figure 7). The lowest acidity (%) was obtained with the application of *Sargassum* with humic acid 5% at 30 and 50 DAP, whereas the highest value for acidity (%) was found in the case of the control. Lower acidity in the harvested product is considered superior for longer storage and consumption.

Foliar application of 2% DAP, 2% MOP, and 0.1% triacontanol 0.05% EC at 30 and 50 DAP resulted in the highest value for tuber hardness (9.45 kg/cm^2), TSS (5.74 °Brix). The specific gravity and Vitamin C content of the tuber were found to be non-significant among the treatments. Nearer-to-neutral pH of the juice was also recorded from the same treatment (Figure 8).

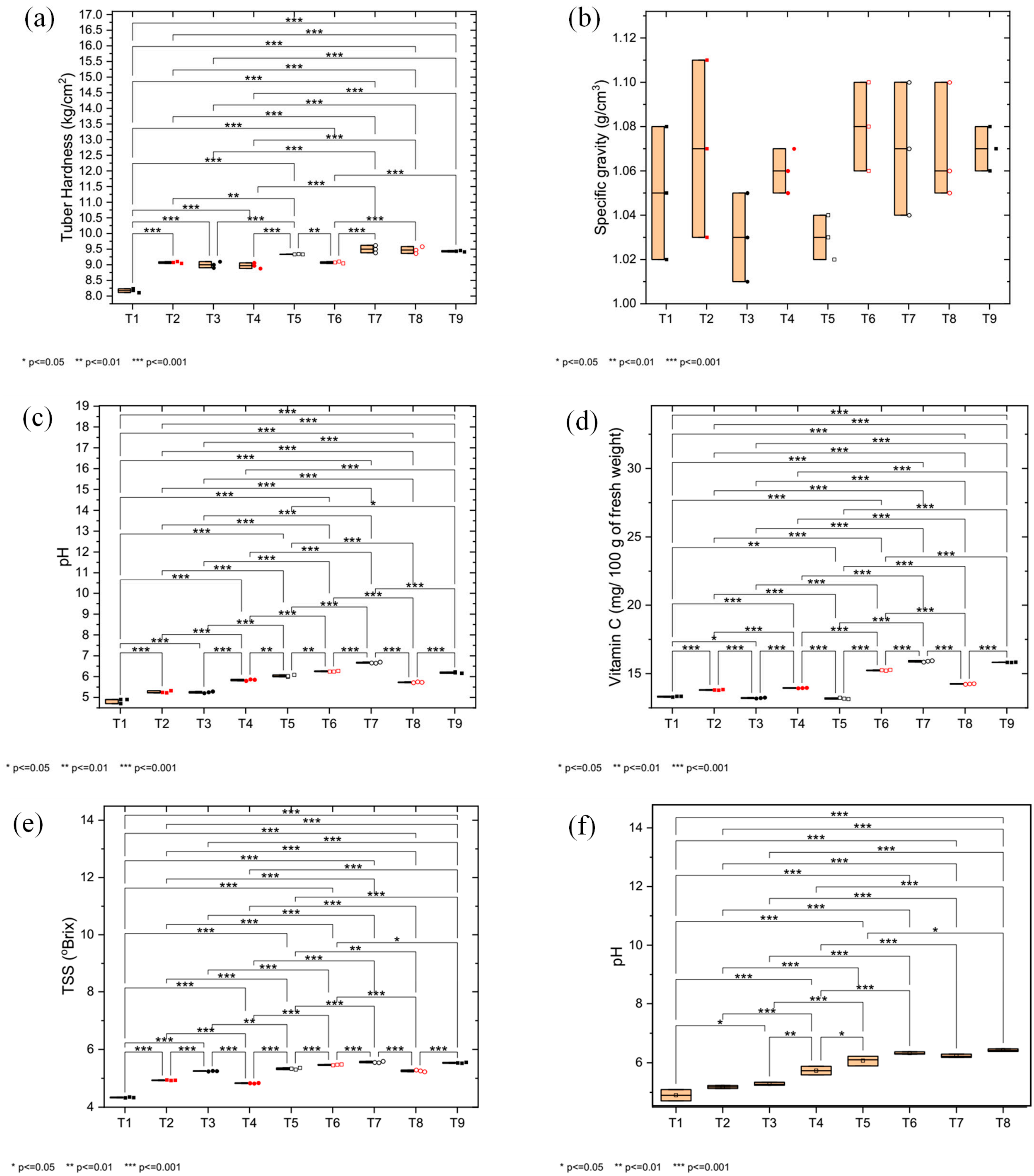

Figure 6. Effect of foliar nutrient management on (**a**) tuber hardness; (**b**) specific gravity; (**c**) pH; (**d**) vitamin C; (**e**) TSS; and (**f**) acidity of potatoes. T1: Control; T2: RDF_{NPK} fb Urea 2% fs $_{30\ DAP}$; T3: RDF_{NPK} fb Urea 2% fs $_{30\ \&\ 50\ DAP}$; T4: RDF_{NPK} fb MOP 2% fs $_{30\ DAP}$; T5: RDF_{NPK} fb Urea 2% fs $_{30\ \&\ 50\ DAP}$ + MOP 2% fs $_{30\ DAP}$; T6: RDF_{NPK} fb Boron 0.1% fs $_{30\ DAP}$; T7: RDF_{NPK} fb Urea 2% fs $_{30\ \&\ 50\ DAP}$ + Boron 0.1% fs $_{30\ DAP}$; T8: RDF_{NPK} fb Zinc 0.5% fs $_{30\ DAP}$; T9: RDF_{NPK} fb Urea 2% fs $_{30\ \&\ 50\ DAP}$ + Zinc 0.5% fs $_{30\ DAP}$.

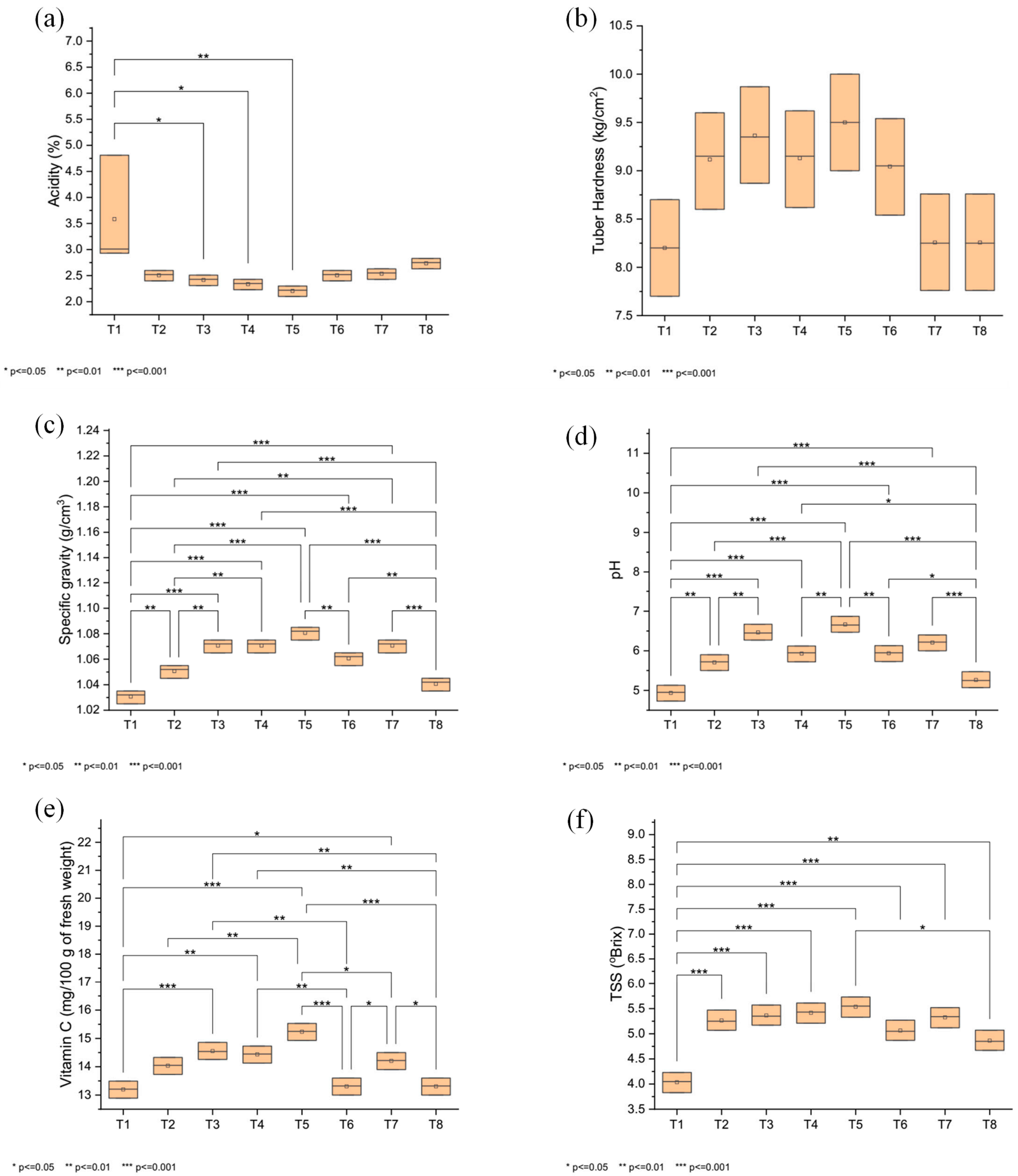

Figure 7. Effect of biostimulants on (**a**) acidity; (**b**) tuber hardness; (**c**) specific gravity; (**d**) pH; (**e**) vitamin C; (**f**) TSS of potatoes (where T1: Control, T2: RDF_{NPK} fb Sargassum 5% fs $_{30\text{ DAP}}$; T3: RDF_{NPK} fb Sargassum 5% fs $_{30\text{ DAP}\ \&\ 50\text{ DAP}}$; T4: RDF_{NPK} fb Sargassum + humic acid 5% fs $_{30\text{ DAP}}$; T5: RDF_{NPK} fb Sargassum + humic acid 5% fs $_{30\text{ DAP}\ \&\ 50\text{ DAP}}$; T6: RDF_{NPK} fb Triacontanol 0.05% fs $_{30\text{ DAP}}$; T7: RDF_{NPK} fb Triacontanol 0.05% fs $_{30\text{ DAP}\ \&\ 50\text{ DAP}}$; T8: Water).

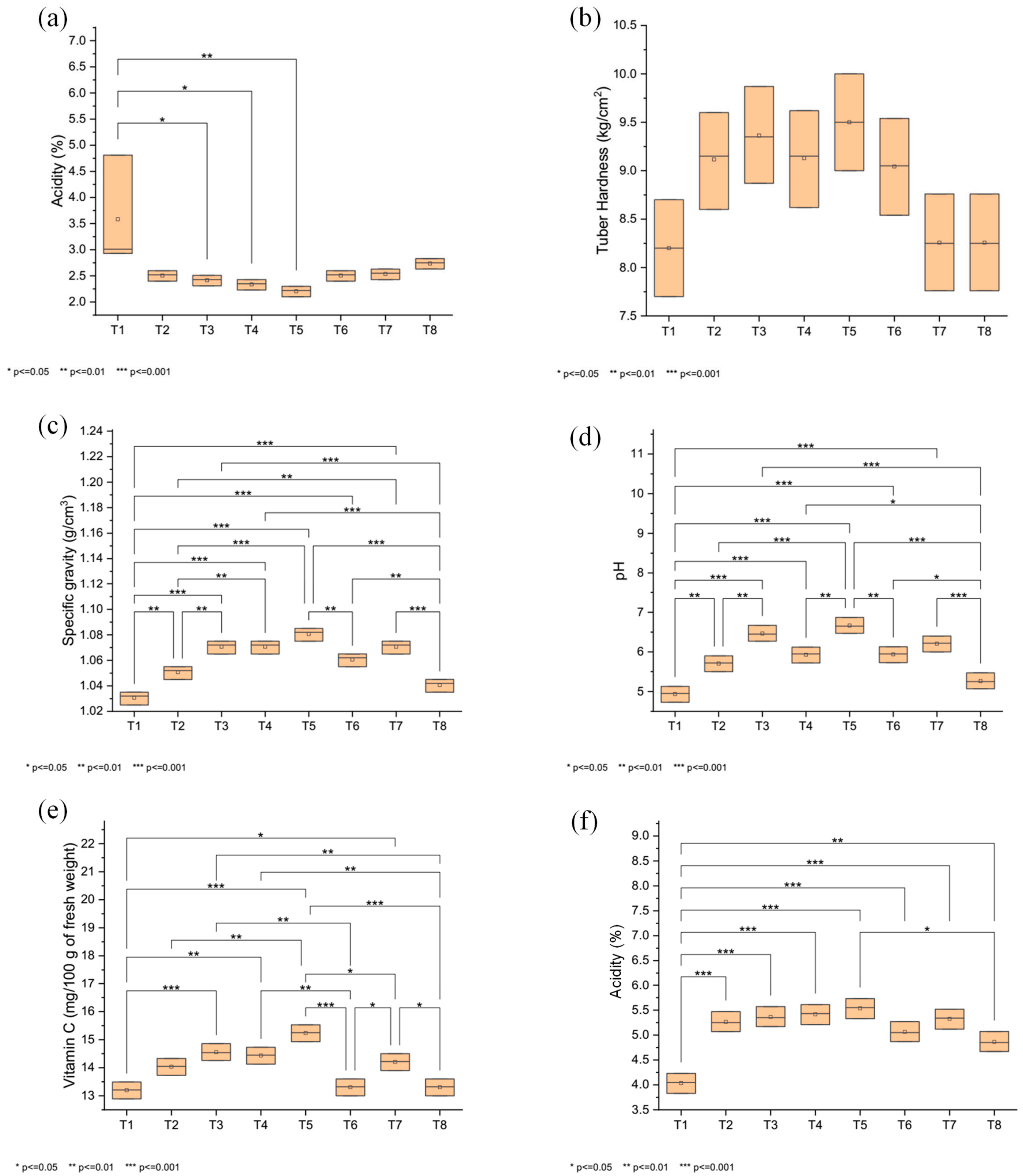

Figure 8. Effect of foliar nutrient and growth regulators on (**a**) tuber hardness; (**b**) specific gravity; (**c**) pH (**d**) vitamin C; (**e**) TSS; (**f**) pH of potatoes (where, T1: Water Spray; T2: 2% DAP at 30 DAP; T3: 2% DAP at 30 And 50 DAP; T4: 2% MOP at 30 DAP; T5: 2% MOP at 30 and 50 DAP; T6: 2% DAP and 2% MOP at 30 DAP; T7: 2% DAP and 2% MOP At 30 and 50 DAP; T8: 2% DAP + 2% MOP + 0.1% Triacontanol 0.05% EC (Miraculan) at 30 and 50 DAP).

3.4. Effect on Soil Moisture and Salinity

The depth-wise periodic soil moisture and salinity in the ZTSM potato fields and adjacent fallow rice fields are presented in Figures 9 and 10, respectively. The periodic moisture depletion at different growth stages from the ZTSM field is significantly slower than that of the bare fallow rice field (Figure 10). On the other hand, the reduction in soil moisture is more significant in the top layer of soil (0–30 cm) than in the lower soil layer.

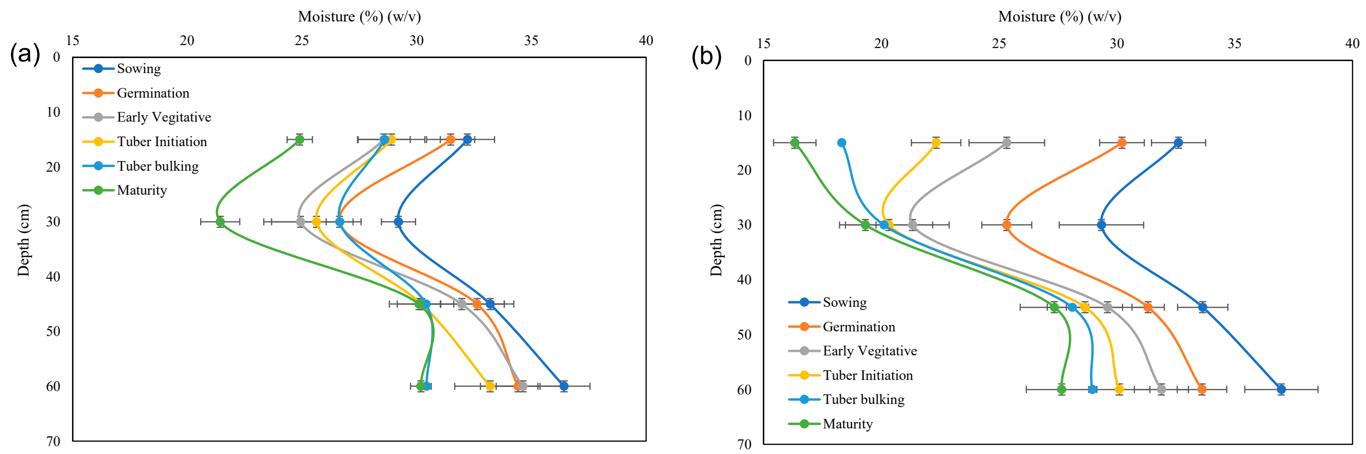

Figure 9. Comparison of soil moisture (%) between (**a**) zero-tilled–mulched potato fields and adjacent (**b**) fallow rice fields (vertical bars indicate the standard deviation of the mean).

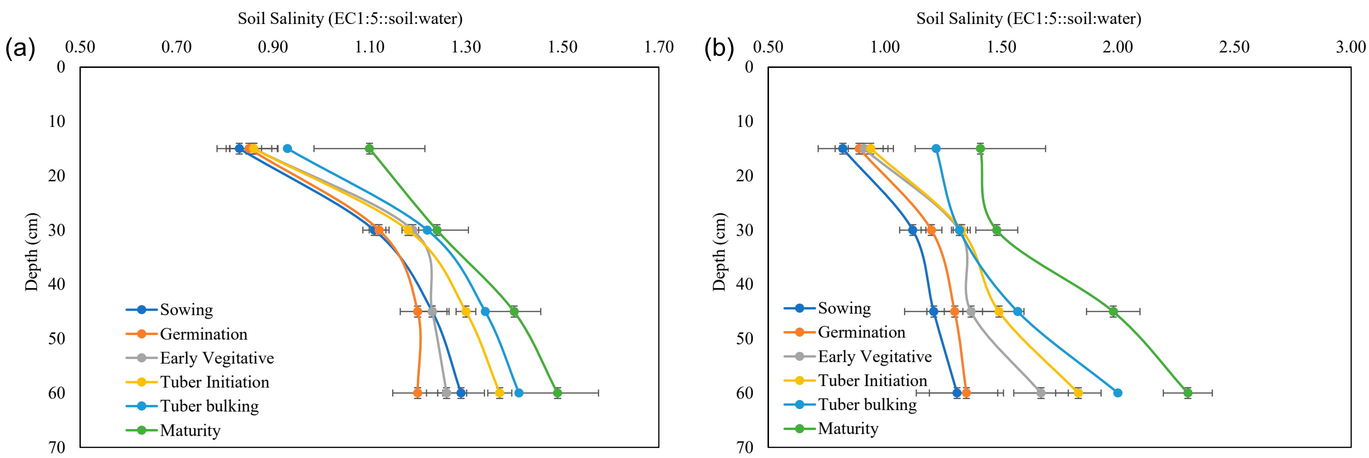

Figure 10. Comparison of soil salinity between (**a**) zero-tilled–mulched potato fields and adjacent (**b**) fallow rice fields (vertical bars indicate the standard deviation of the mean).

From the results, it was observed that salinity development in the fallow rice fields was significantly faster than in the ZTSM potato fields (Figure 10). So, due to the low salinity in the zero-tilled–mulched fields, the potato crop was able to withstand the salinity and, ultimately, showed sustained growth and yield performances.

3.5. Field Demonstration

The large-scale field demonstration of potato cultivation under ZTSM in different villages of Indian Sundarbans to conserve soil and water, limit evaporation losses, and eventually reduce salinity buildup in the topsoil was conducted. In the initial years, the farmers encountered several studies for evaluating the suitability of the ZTSM system in the coastal agroecosystem, followed by its demonstration, with various aspects in numerous areas in the polders (Figure 11). Later, in the experimental research, various field demonstration programs were conducted with several farmers to validate the technology.

The field demonstration of the zero-tillage and straw mulching potato cultivation system was conducted for 1026 farmers in Gosaba block from 2022 to 2024, covering an area of more than 15 ha (Table 5). Apart from all the technical support, each farmer was provided with true-type potato seeds (*Kufri Pukhraj*) for ZTSM potato cultivation, and other nutrient and plant protection inputs.

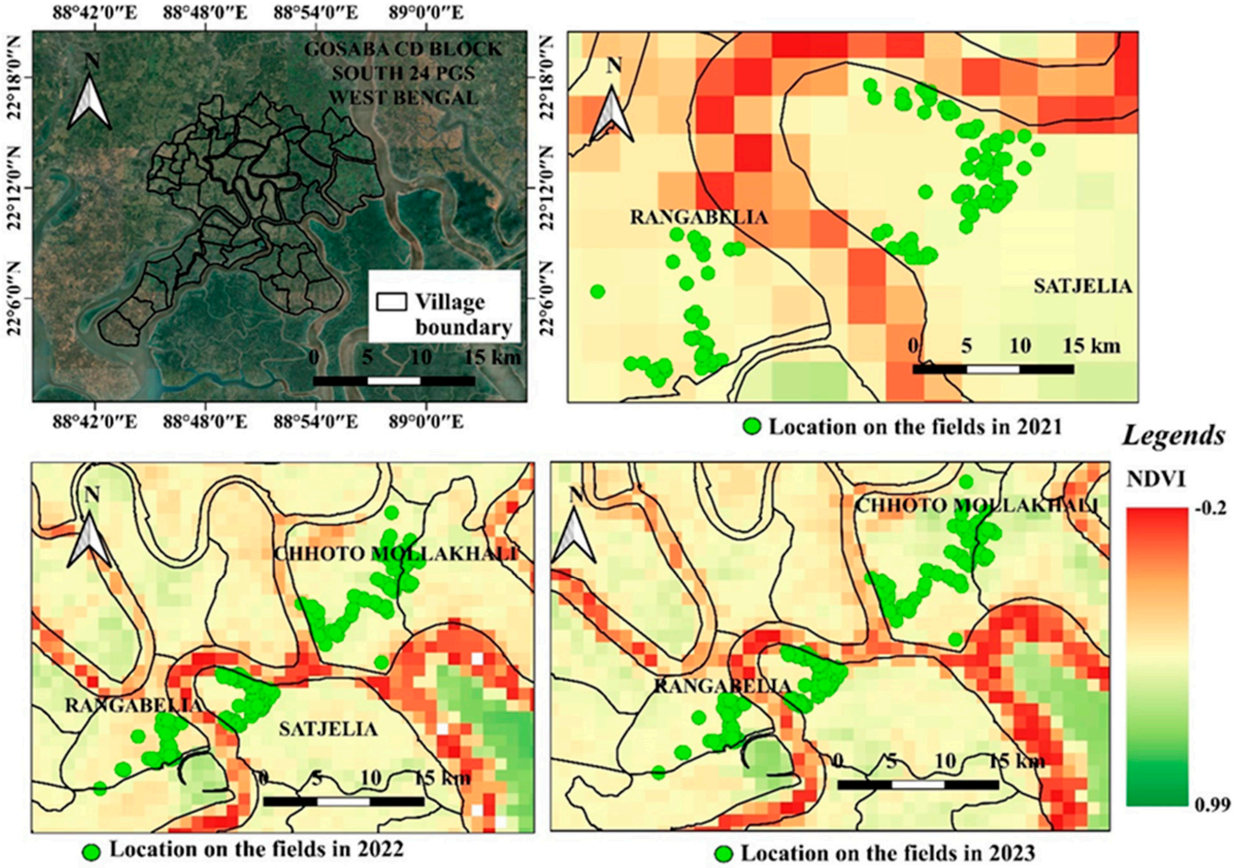

Figure 11. Location and spatial distribution of ZTSM potato field across the various experimental sites of Indian Sundarbans (Site-I: Rangabelia, Site-II: Choto Mollakhali, and Site-III: Satjelia).

Table 5. Field demonstration of zero-tillage potato.

Sl. No	Year	Variety	Demonstration Location	Area (ha)	Farmers Involved		
					Male	Female	Total
1	2020–2021	*Kufri pukhraj*	Rangabelia (Site-I)	4.2	95	76	171
2	2021–2022	*Kufri pukhraj*	Rangabelia (Site-I) Satjelia (Site-II)	3.06	142	88	230
3	2022–2023	*Kufri pukhraj*	Rangabelia (Site-I) Satjelia (Site-II) Choto Mollakhali (Site-III)	4.33	195	130	325
4	2023–2024	*Kufri pukhraj*	Rangabelia (Site-I) Satjelia (Site-II) Choto Mollakhali (Site-III)	4.00	195	105	300

Zero-tillage potato cultivation technology has emerged as one of the most promising soil and water conservation techniques for cultivating potatoes in coastal saline zones. The first demonstration trial was conducted with 171 farmers in an area measuring 4.2 ha in three different locations in the Indian Sundarbans Delta, in 2020–2021. Later, 230 farmers in an area measuring 3.06 ha, in 2021–2022, 325 farmers in an area measuring 4.33 ha, and

300 farmers in an area measuring 4.00 ha were included in the demonstration trials. The yield and economics of zero-tillage potatoes under straw mulch conditions showed very close performance at both the demonstration sites. However, the yield was still below the yield potential demonstrated in the experimental field at Site-I, for the three consecutive seasons (19.6 t/ha, 20.7 t/ha, and 14.0 t/ha in 2021, 2022, and 2023, respectively). This is most probably due to the inexperience of the farmers, a portion of whom were women who had previously received little training in crop cultivation. However, there were large variations in crop management practices, which was reflected in the higher variability in yield and economics in the last years (especially at Site-III).

The probability exceedance analysis shows that in 2022, there was hardly any difference between Site-II and Site-III (Figure 12a), where the demonstrations were primarily organized. However, in 2023, Site-III showed a higher probability of securing a higher yield (Figure 12b). It also showed higher stability in yield than Site-II. This is probably due to the assured water source at Site-III and a higher level of rodent infestation at Site-II.

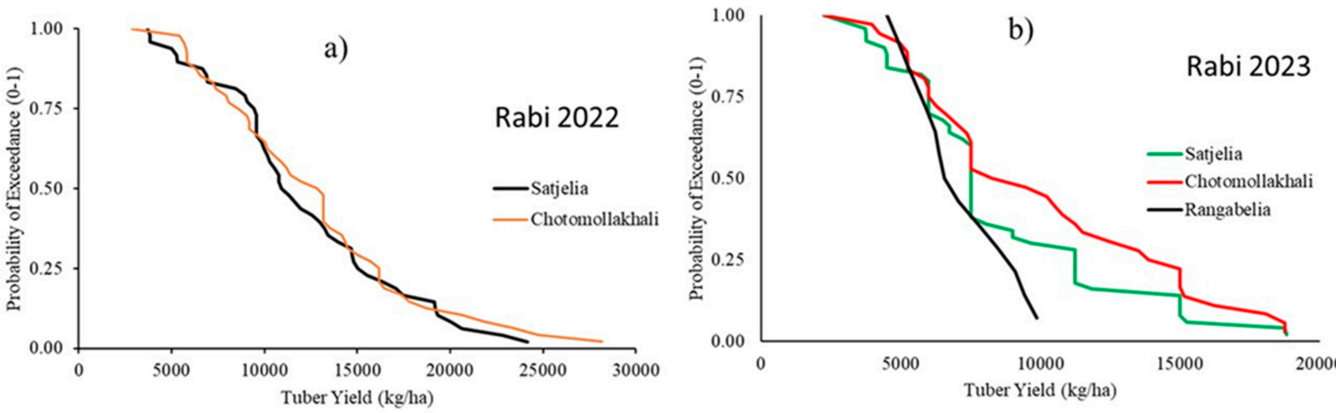

Figure 12. Probability of exceedance (0–1) of potato tuber yield (kg/ha) across different locations in (**a**) *Rabi*, 2022, and (**b**) *Rabi*, 2023.

However, in the season of 2023–2024, the yield (7.2 t/ha, 8.7 t/ha, and 9.9 t/ha) of the zero-tillage potatoes at Site-I, Site-II, and Site-III decreased significantly compared to the yield for the 2022–2023 cropping season (14.0 t/ha, 12.2 t/ha, and 12.8 t/ha, respectively) (Table 6). The significant decline in yield in *Rabi* for 2023-2024, was due to a massive rat attack in the crop field and a lack of proper rodent management practices (100% of the farmers reported the rodent attack in the crop field). Two spells of rain in the late crop growth stage led to infestation by fungal diseases like late blight. However, both the (notional) gross and net return marginally increased at Site-II and Site-III because of a stable potato price in the market and the reduced cost of cultivation. There were no significant differences between the sites in different years of field demonstration (Supplementary Table S2).

Table 6. Yield and economics of zero-tillage potato cultivation (2022–2023 and 2023–2024).

Location	N	Year	Yield (t/ha)	Gross Return (INR per ha)	Net Return (INR per ha)	B:C Ratio
Satjelia	57	2022–23	12.28 (±5.31)	147,321 (±63,694)	94,701 (±47,886)	2.88 (±0.71)
	50	2023–24	8.7 (±4.32)	157,324 (±51,858)	104,400 (±51,919)	2.97 (±0.99)

Table 6. *Cont.*

Location	N	Year	Yield (t/ha)	Gross Return (INR per ha)	Net Return (INR per ha)	B:C Ratio
Choto Mollakhali	58	2022–23	12.85 (±5.93)	154,153 (±71,215)	89,830 (±60,615)	2.73 (±1.17)
	36	2023–24	9.9 (±4.70)	205,461 (±66,220)	131,833 (±65,652)	2.79 (±0.88)
Rangabelia	10	2022–23	14.00 (±1.00)	205,411 (±18,216)	117,447 (±13,309)	2.68 (±0.19)
	14	2023–24	7.2 (±1.96)	161,228 (±24,313)	87,576 (±24,112)	2.18 (±0.32)

3.6. Potential Adoption of the Innovation

The ZTSM was demonstrated for a large number of farms in three islands of the Indian Sundarbans during 2022–23 to 2023–24, which created a spillover effect on the neighboring farmers and islands. An estimation of the potential adoption of the innovation in the project locations using the ADOPT tool suggests that a peak adoption level of 98% by the eighth year is likely to be achieved (Figure 13). While achieving this peak adoption level, ADOPT identified "enterprise scale" (Question 4, meaning, "what proportion of the target households depend highly for their livelihood on ZTSM that could benefit from the innovation") as the most sensitive factor to shape the "peak adoption level". Similarly, "relevant existing skills and knowledge" (Question 12, meaning "What proportion of the target households will need to develop substantial new skills and knowledge to use ZTSM?") was identified as the most sensitive factor influencing the "time to peak adoption level". Reducing the input in the ADOPT model by one level of the response scale for Question 4 (conservative scenario) and Questions 4 and 12 together (pessimistic scenario) showed a lowered, but impressive technology adoption. In the conservative and pessimistic scenarios, ZTSM is likely to be adopted by 95% and 98% of the target population by the eighth and ninth year, respectively. However, in a pessimistic scenario, the adoption in the first five years will be less (69%) than in the other two scenarios (80% and 83%).

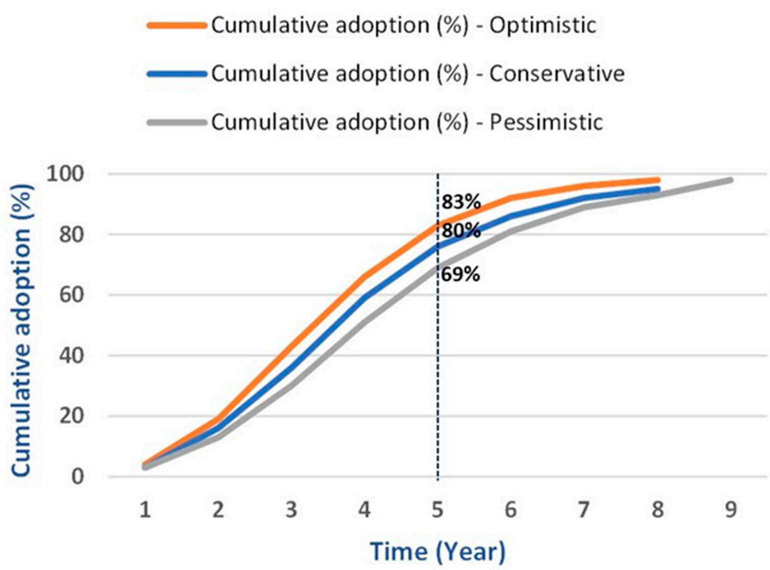

Figure 13. Peak adoption level (%) and peak time to adoption (year) for zero tillage and straw mulching (ZTSM) potato cultivation for three scenarios. Scenarios are defined by the perceived "step-up" and "step-down" options of the ADOPT model. The figures on the right of the dotted vertical line suggest the likely rate of adoption in the first five years.

4. Discussions

4.1. Zero-Tillage Potato as Low-Cost Intensification Technology

The cultivation of potatoes in the zero-tillage mulch system has proven to be a sustainable agronomic strategy for cropping system intensification in the Indian Sundarbans Delta. This technology is not new to the farming community of the Delta, but it lacks a scientific rationale. However, with robust field research, farmers have been made aware of the effectiveness of this low-cost technology for enhancing the area's food and nutritional security [42]. Generally, the cultivation of potatoes requires a significant amount of manpower and energy to perform various intercultural operations, like the earthing up and harvesting of tubers, which limits the entry of women into the production system. With the implementation of this low-energy-intensiveness technology, more women have shown an interest in engaging with potato farming, making it a gender-neutral technology [43]. Generally, after the harvest of rainy season rice, due to the wetness of the soil, it takes much time to return the soil to working conditions for land preparation [44]. The ZTSM potato cultivation system promotes the early establishment of potatoes with less rigorous tillage and with better utilization of the sowing window and the prevalent weather conditions. Seed tubers can be directly planted after rice harvest without compromising the optimal sowing time [29]. Additionally, part of the significant quantity of straw generated from rice harvesting (around 17 Mt in West Bengal alone) may be recycled as mulch material for the upcoming winter season, as well as reducing the emerging problem of stubble burning [45]. The addition of on-farm inputs, such as mulching materials, including paddy straw, increases resource use efficiency and allows them to decompose over the soil [11]. Since the decomposition of organic material takes place, it enhances the water-holding capacity by the addition of organic matter into the soil, which is also imperative for improving soil health, both physiochemically and biologically. Organic mulching is a critical agronomic practice that conserves moisture by protecting the soil from direct sunlight, thereby reducing evaporation [46]. Simultaneously, it provides nutrients as the organic material decomposes and suppresses weed growth through a protective soil barrier [44]. The residual soil moisture from the preceding *Kharif* rice crop is efficiently utilized to accelerate tuber germination under zero-tillage conditions. This enhances soil moisture retention and ensures the prevention of upward soil salinity movement, contributing to superior growth and development compared to conventional potato cultivation. As potato tubers develop beneath the straw mulch, maintaining adequate mulch coverage is imperative to prevent solanine accumulation and tuber greening. Several studies conducted over the different regions of the country determined that potato tuber yields under zero-tillage system management were enhanced by 20% or more compared with potatoes cultivated under non-mulch conditions [47,48].

Additionally, this method significantly decreases the need for irrigation (2–3 irrigations for zero-tillage potatoes and 6–7 irrigations for conventional cultivation) and labor compared to conventional tillage, which necessitates thorough soil preparation, including ridge and furrow formation, which is only possible after rice harvest and soil moisture reduction [29]. The potato, being a heavy feeder crop, requires a huge number of fertilizers to fulfil its nutrient demand. However, in this technology, the essential nutrients are foliar-applied during the critical stages, apart from the organic manure used during sowing, which acts as a continuous nutrient supply [49]. Hence, this sustainable technology has inspired many farmers across the Delta to implement it and to intensify the fallow areas that were earlier shown as gray, and now turning green year after year under satellite and NDVI imagery (Figure 11). In general, the net return from conventional-tillage potato cultivation is higher than that of the ZTSM (zero tillage and straw mulching) potato production system due to its higher yield. However, owing to the significantly lower cost of cultivation, the

BCR is higher in the ZTSM system. A detailed economic analysis comparing ZTSM and conventional tillage methods is provided in Supplementary Table S2.

4.2. Performance of ZTSM POTATO

The performance of potatoes under the ZTSM system, in terms of crop growth, yield, and tuber quality, was improved by applying various foliar nutrients and biostimulants throughout the research experiments (Figures 2–10 and Tables 1–4). All these treatments make potato cultivation profitable under zero-tillage system management. Despite the various constraints, a potato yield of 11–26 t/ha was obtained throughout the experiments. This result was similar to the study conducted by Ramirez et al. [50].

The combined application of chemical fertilizers and organic amendments supply nutrients efficiently to the plant for their growth and development [51]. The application of nutritional inputs during the critical growth stages, such as establishment, tuber formation, and tuber bulking, increases the crop nutritional uptake [52]. Due to the constraint of applying fertilizers directly in the soil, the crop performance was found to be sub-optimal, and it was enhanced due to the supplementation of various nutrients through the foliar application of nutrients to meet the nutrient demands of the crop [49].

The present experiments revealed that the foliar application of macro and micronutrients, along with various growth stimulators, improved the nutrient use efficiency because of the better absorption of nutrients by the leaf surface, owing to its reduced particle size and increased surface area, thereby increasing the leaf chlorophyll content, as well as metabolic and biochemical activities like photosynthesis, hormonal balance, and enzymatic regulation [43]. The increase in plant growth characteristics like plant height, dry matter accumulation, number of compound leaves, and leaf area index, might be due to the increased uptake of nitrogen, phosphorous, potassium, and micronutrients through the foliar application of urea, MOP, and DAP, along with micronutrients [49]. The application of biostimulants like seaweed extracts and humic acid enhanced the overall physiology of the plant, leading to better uptake of essential plant nutrients and improving the plant immune system. As a result, foliar fertilization with different sources of macro and micronutrients, as well as other biostimulants, enhanced the yield components and yield, which could be attributed to its role in energy metabolism and enzyme activation, which increases the exchange rate and nitrogen activity in the plant body [53]. This result agrees with the findings of Sarangi et al. [23]. Moreover, the application of the recommended amount of mulching material for potato cultivation not only enhances crop growth and development, but also has a significant impact on tuber quality, more specifically, the fiber content.

Foliar-applied potassium contributed to improved stomatal activity, reduced transpiration, and increased cellular water retention, all supporting higher yield. Nitrogen foliar sprays further boosted photosynthesis and nutrient reallocation, directly benefiting tuber production [54]. In our studies, different sources of nutrients and biostimulants applied with foliar spray at different stages increased several of the tuber quality parameters of the potatoes, including tuber hardness (kg/cm^2), specific gravity (g/cm^3), TSS (°Brix), juice pH, total acidity of juice (%), and vitamin C content (mg/100 g of fresh weight). A similar result was indicated by Sarangi et al. [29]. As foliar sprays, various biostimulants were applied during the early vegetative and tuber initiation stages. These included humic acid, triacontanol, and sargassum-based seaweed extract, serving as sources of N-P_2O_5-K_2O and plant growth stimulators, which may have influenced the tuber quality parameters. The application of triacontanol significantly enhanced the dry matter accumulation and leaf area index (LAI), accelerated the tuber bulking rate, and promoted the formation of larger tubers, collectively leading to an increase in overall potato yield [55]. The application of seaweed extract demonstrated significant effects on the growth and yield of the potato tubers. Seaweed extract enhances tuber development by promoting root biomass, increasing nutrient assimilation, and enhancing abiotic stress resilience, accelerating the tuber bulking rate and improving tuber size. Rich in bioactive compounds such as phytohormones (auxins, cytokinins, gibberellins), minerals, and antioxidants, seaweed extract facilitates physiological and biochemical processes that optimize tuber yield and quality [56].

4.3. Soil Salinity and Soil Moisture Retention

The straw mulching used in zero-tillage technology conserves soil moisture and restricts the buildup of salinity in the top layers of soil [29]. In our present research, the soil salinity was observed to increase with the increasing depth of the sampling. Surface mulching has a significant and positive impact on regulating soil salinity by reducing evapotranspiration. Zero tillage and mulching act as barriers to diminish the evaporation from the top layer of soil by reducing the capillary rising of soil water [44], as well as the soluble salts from the groundwater, resulting in the retention of moisture in soil and preventing salinity upsurge during the dry period of winter [57]. Apart from the mechanism of mulching in moisture rendition and low salinity buildup, the application of a huge load of organic manure during seed tuber sowing could be a possible reason for this. Organic manure is known to increase the water-holding capacity of the soil by improving the soil's physical properties, like its structure, bulk density, porosity, etc. [58], and also to ameliorate soil salinity to some extent [59].

4.4. Adoption of the Innovation

The implementation of the Zero-Tillage System of Management (ZTSM) in the Indian Sundarbans (2022–2024) generated significant spillover effects, promoting widespread adoption among neighboring farmers. The projected peak adoption rate of 98% by the eighth year demonstrates ZTSM's high scalability and adaptability in the region. The salience of the "enterprise scale" highlights the importance of aligning ZTSM with the economic needs of farming households, perhaps by enhancing its area and income share for practicing farmers. The critical importance of the enterprise scale has been reported in old [60] and recent [61] studies, although reports from South Asian countries are not common. Even in conservative and pessimistic projections, adoption rates remained robust, reaffirming ZTSM's economic relevance. "Existing skills and knowledge" influence the rate of adoption and could slow early adoption, which could be addressed by making the training modules available with the grassroots-level extension. This observation was made even in the local context [62], and the critical importance of advisory support is supreme in ensuring direct and spillover effects on farming communities [63]. Although initial adoption may be slower under certain conditions, near-universal adoption is anticipated by the ninth year. To maintain this momentum, targeted interventions, such as the provision of advice for farmers and increased acreage at the individual and landscape levels, are essential for reinforcing the practical benefits of the ZTSM.

4.5. Limitation and Future Strategies

The ZTSM potato production technology is emerging as a sustainable alternative for potato cultivation in the resource-challenged Indo-Gangetic deltas of India and Bangladesh [29,50,64–68] (Supplementary Table S3). This method significantly reduces land preparation costs and environmental degradation compared to conventional practices [64]. Research indicates that zero tillage combined with mulching can enhance soil organic matter and improve productivity in saline regions. However, this method still presents certain limitations that require further research, including suboptimal yield levels compared to conventional potato production, higher susceptibility to rodent damage, and crop loss due to winter rainfall. Additionally, the standardization of seed tuber supply chains in remote coastal regions remains a crucial challenge. Despite these constraints, ZTSM potato cultivation has the potential to increase cropping intensity and farm income while contributing to environmental sustainability in fragile agro-ecosystems.

5. Conclusions

- The results revealed that *Kufri Chandramukhi* performed the best among all the tested potato varieties. However, *Kufri Pukhraj* was selected for the upcoming experiment due to its short duration and early bulking rate. The highest growth, yield, and quality of potato was achieved with the application of 2% urea at 30 and 50 days after planting, along with 0.1% boron applied 30 days after planting in the ZTSM potato cultivation. Among the biostimulant treatments, the foliar application of 5% *Sargassum*-based seaweed extract and humic acid at 30 and 50 days after planting recorded the highest growth, yield, and quality parameters of potatoes under zero-tillage systems of management and, in the case of various foliar nutrients and growth regulators, the combined application of 2% days after planting, 2% MOP, and 0.1% triacontanol 0.05% EC at 30 and 50 days after planting led to the recording of the highest of all the growth, yield and quality parameters. The technology was widely accepted and adapted by the farming community, with an increase in practicing farmers from 23 to 1100, covering an area measuring 15 ha.
- The Zero-Tillage System of Management (ZTSM) for potato cultivation offers a low-cost, sustainable intensification strategy in the Indian Sundarbans, enhancing food and nutritional security for a large number of smallholder farmers in the region.
- ZTSM optimizes sowing windows and resource utilization and manages risks for smallholders. It results in positive ecosystem services by saving water, improving soil health, and preventing weed growth and salinity buildup.
- ZTSM accommodates the greater participation of women, without adding to their workload, thus offsetting labor crises in the region, which has a historically high incidence of male outmigration.
- The significant greening of previously fallow lands in the region demonstrates ZTSM's role in landscape-scale agricultural transformation. The innovation presents a transformative opportunity for sustainable agriculture in the Indian Sundarbans. However, realizing its full potential requires strategic investments in farmer education, targeted advisory, and economic integration to achieve widespread, enduring impact. The widespread adoption of ZTSM requires supportive policies emphasizing resource efficiency, gender inclusion, and sustainable farming practices.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land14030563/s1. Supplementary Table S1: Details of the experiments, Supplementary Table S2: The detailed economic analysis comparing ZTSM vs. conventional methods, Supplementary Table S3: A comparative analysis of ZTSM system of potato cultivation, Supplementary Table S4: Comparisons between the different experimental sites.

Author Contributions: Conceptualization, S.S., K.B., R.G. and M.M.; methodology, S.S., K.B., R.G. and M.M.; software, S.S., R.G., S.D., A.D. and A.G.; validation, S.S., K.B., R.G. and M.M.; formal analysis, S.D., S.S., K.B. and R.G.; investigation, S.S., K.B., R.G., M.M. and S.S.; resources, S.S., K.B., R.G. and M.M.; data curation, S.S., R.G., K.B., S.D. and A.D.; writing—original draft preparation, S.S., R.G., S.D. and A.D.; writing—review and editing, S.S., K.B., R.G. and M.M.; visualization, S.S., R.G., S.D., A.D. and A.G.; supervision, S.S., K.B., R.G. and M.M.; project administration, S.S., K.B., R.G. and M.M.; funding acquisition, M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Australian Centre for International Agricultural Research (ACIAR), Australia through the project, "Cropping system intensification in the salt-affected coastal zones of Bangladesh and West Bengal, India (LWR/2014/073) and the Department of Foreign Affairs and Trade (DFAT), Government of Australia through the SciTech4Climate Indo-Pacific Climate-Smart Agriculture Initiative: Project B: 'Ganges coastal zone climate smart agricultural production" (OD-227626), with co-investment from the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: Farmers of the Gosaba Island, who participated in the research trials, are duly acknowledged.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Kundu, R.; Brahmachari, K.; Roychoudhury, S. Nutrient management in rice-lentil (paira)-sesame cropping system under coastal saline zone of West Bengal. *Int. J. Agric. Sci.* **2012**, *8*, 320–324.
2. Mandal, S.; Maji, B.; Sarangi, S.K.; Mahanta, K.K.; Mandal, U.K.; Burman, D.; Digar, S.; Mainuddin, M.; Sharma, P.C. Economics of cropping system intensification for small-holder farmers in coastal salt-affected areas in West Bengal: Options, challenges and determinants. *Decision* **2020**, *47*, 19–33. [CrossRef]
3. Kumar, P.; Sarangi, S.K.; Mahajan, G.R.; Das, B.; Uthappa, A.R.; Desai, S.; Paramesh, V. Paradigm shift in coastal agricultural research: From production to risk management. *Indian J. Agron.* **2023**, *68*, S198–S211.
4. Bandyopadhyay, B.K.; Burman, D.; Mandal, S. Improving agricultural productivity in degraded coastal land of India-experiences gained and lessons learned. *J. Indian Soc. Coast. Agric. Res.* **2011**, *29*, 1–9.
5. Mandal, S.; Sarangi, S.K.; Burman, D.; Bandyopadhyay, B.K.; Maji, B.; Mandal, U.K.; Sharma, D.K. Land shaping models for enhancing agricultural productivity in salt-affected coastal areas of West Bengal-An economic analysis. *Indian J. Agric. Econ.* **2013**, *68*, 389–401.
6. Burman, D.; Mandal, S.; Bandopadhyay, B.K.; Maji, B.; Sharma, D.K.; Mahanta, K.K.; Sarangi, S.K.; Mandal, U.K.; Patra, S.; De, S.; et al. Unlocking production potential of degraded coastal land through innovative land management practices: A synthesis. *J. Soil Salin. Water Qual.* **2015**, *7*, 12–18.
7. Campbell, J.; Whittingham, E.; Townsley, P. Responding to coastal poverty: Should we be doing things differently or doing different things. In *Environment and Livelihoods in Tropical Coastal Zones*; CABI: Wallingford, UK, 2006; pp. 274–292.
8. Tenhunen, S.; Uddin, M.J.; Roy, D. Confronting Climate Change in the Sundarbans in Coastal India and Bangladesh. *Wisdom Lett.* **2024**, *2024*. [CrossRef]
9. Sarkar, S.; Brahmachari, K.; Gaydon, D.S.; Dhar, A.; Dey, S.; Mainuddin, M. Options for Intensification of Cropping System in Coastal Saline Ecosystem: Inclusion of Grain Legumes in Rice-Based Cropping System. *Soil Syst.* **2024**, *8*, 90. [CrossRef]
10. Humphreys, A.; Gorsky, A.L.; Bilkovic, D.M.; Chambers, R.M. Changes in plant communities of low-salinity tidal marshes in response to sea-level rise. *Ecosphere* **2021**, *12*, e03630. [CrossRef]
11. Paul PL, C.; Bell, R.W.; Barrett-Lennard, E.G.; Kabir, E. Straw mulch and irrigation affect solute potential and sunflower yield in a heavy textured soil in the Ganges Delta. *Agric. Water Manag.* **2020**, *239*, 106211. [CrossRef]
12. Sarkar, S.; Gaydon, D.S.; Dey, S.; Chaki, A.K.; Brahmachari, K.; Dhar, A.; Garai, S.; Mainuddin, M. Evaluation of the APSIM Model in Rice-Lentil Cropping System in a Complex Coastal Saline Environment. *J. Indian Soc. Coast. Agric. Res.* **2024**, *42*, 53–72. [CrossRef]
13. Dagar, J.C.; Sharma, P.C.; Chaudhari, S.K.; Jat, H.S.; Ahamad, S. Climate change vis-a-vis saline agriculture: Impact and adaptation strategies. *Innov. Saline Agric.* **2016**, 5–53. [CrossRef]
14. Mondal, R.I.; Begum, F.; Aziz, A.; Sharif, S.H. Crop sequences for increasing cropping intensity and productivity. *SAARC J. Agric.* **2015**, *13*, 135–147. [CrossRef]
15. Singh, B.P.; Singh, B.; Lal, M.K. Seven decades of potato research in India: Achievements and future thrusts. *Int. J. Innov. Hortic.* **2022**, *11*, 158–183. [CrossRef]
16. Rana, R.K.; Anwer, M.D. Potato production scenario and analysis of its total factor productivity in India. *Indian J. Agric. Sci.* **2018**, *88*, 1354–1361. [CrossRef]
17. Bajracharya, M.; Sapkota, M. Profitability and productivity of potato (*Solanum tuberosum*) in Baglung district, Nepal. *Agric. Food Secur.* **2017**, *6*, 47. [CrossRef]
18. Jasim, A.H.; Hussein, M.J.; Nayef, M.N. Effect of foliar fertilizer (high in potash) on growth and yield of seven potato cultivars (*Solanum tuberosom* L.). *Euphrates J. Agric. Sci.* **2013**, *5*, 1–7.

19. Meena, B.P.; Kumar, A.; Lal, B.; Meena, R.L.; Shirale, A.O.; Dotaniya, M.L.; Kumar, K.; Sinha, N.K.; Meena, S.N.; Asha, R.; et al. Sustainability of popcorn-potato cropping system improves due to organic manure application and its effect on soil health. *Potato Res.* **2019**, *62*, 253–279. [CrossRef]
20. Kumar, R.; Mishra, J.S.; Upadhyay, P.K.; Hans, H. Rice fallows in the eastern India: Problems and prospects. *Indian J. Agric. Sci.* **2019**, *89*, 567–577. [CrossRef]
21. Mangalassery, S.; Sjögersten, S.; Sparkes, D.L.; Sturrock, C.J.; Craigon, J.; Mooney, S.J. To what extent can zero tillage lead to a reduction in greenhouse gas emissions from temperate soils? *Sci. Rep.* **2014**, *4*, 4586. [CrossRef]
22. Zhao, X.; Liu, S.L.; Pu, C.; Zhang, X.Q.; Xue, J.F.; Zhang, R.; Wang, Y.Q.; Lal, R.; Zhang, H.L.; Chen, F. Methane and nitrous oxide emissions under no-till farming in China: A meta-analysis. *Glob. Change Biol.* **2016**, *22*, 1372–1384. [CrossRef] [PubMed]
23. Sarangi, S.K.; Singh, S.; Kumar, V.; Srivastava, A.K.; Sharma, P.C.; Johnson, D.E. Tillage and crop establishment options for enhancing the productivity, profitability, and resource use efficiency of rice-rabi systems of the salt-affected coastal lowlands of eastern India. *Field Crops Res.* **2020**, *247*, 107494. [CrossRef]
24. Zuber, S.M.; Villamil, M.B. Meta-analysis approach to assess effect of tillage on microbial biomass and enzyme activities. *Soil Biol. Biochem.* **2016**, *97*, 176–187. [CrossRef]
25. Sarangi, S.K.; Maji, B.; Sharma, P.C.; Digar, S.; Mahanta, K.K.; Burman, D.; Mandal, U.K.; Mandal, S.; Mainuddin, M. Potato (*Solanum tuberosum* L.) cultivation by zero tillage and paddy straw mulching in the saline soils of the Ganges Delta. *Potato Res.* **2021**, *64*, 277–305. [CrossRef]
26. Mainuddin, M.; Bell, R.W.; Sarangi, S.K.; Maniruzzaman, M.; Pena-Arancibia, J.L.; Gaydon, D.S.; Karim, F.; Monjardino, M.; Glover, M.; Brahmachari, K.; et al. Mitigating risk and scaling-out profitable cropping system intensification practices in the salt-affected coastal zone of the Ganges Delta. *J. Indian Soc. Coast. Agric. Res.* **2024**, *42*, 1–13. [CrossRef]
27. Census of India. District Census Handbook: South 24 Parganas, Village and Town Wise Primary Census Abstract, Series 20, Part XII-B, Directorate of Census Operation, Govt. of West Bengal. New Delhi: Census of India. 2011. Available online: www.censusindia.gov.in (accessed on 20 May 2020).
28. Mila, A.J.; Bell, R.W.; Barrett-Lennard, E.G.; Kabir, E. Salinity dynamics and water availability in water bodies over a dry season in the Ganges Delta. *Future Sustain. Agric. Saline Environ.* **2021**, 305–322. [CrossRef]
29. Sarangi, S.K.; Mainuddin, M.; Bell, R.W.; Digar, S. Rice-zero tillage potato-green gram and conservation agriculture enable sustainable intensification in the Coastal Region. *J. Indian Soc. Coast. Agric. Res.* **2024**, *42*. [CrossRef]
30. Pandey, N.K.; Kharumnuid, P.; Kumar, S.; Chakrabarti, S.K.; Bhardwaj, V. Economic Impact of Early Bulking and Drought-Tolerant Potato Cultivar Kufri Pukhraj in India. *Potato Res.* **2024**, *67*, 1469–1482. [CrossRef]
31. Tyl, C.; Sadler, G.D. pH and titratable acidity. *Food Anal.* **2017**, *4*, 389–406.
32. Casanas, R.; González, M.; Rodríguez, E.; Marrero, A.; Díaz, C. Chemo−metric studies of chemical compounds in five cultivars of potatoes from Tenerife. *J. Agric. Food Chem.* **2002**, *50*, 2076–2082. [CrossRef]
33. Gould, W.A. Specific gravity of potatoes. In *Potato Production, Processing and Technology*; CTI Publications Inc.: Baltimore, MD, USA, 1999; pp. 51–72.
34. Westermann, D.; James, D.; Tindall, T.; Hurst, R. Nitrogen and Potassium fertilization of potatoes: Yield and specific gravity. *Am. Potato J.* **1994**, *71*, 417–432. [CrossRef]
35. Bouyoucos, G.J. Hydrometer method improved for making particle size analyses of soils. *Agron. J.* **1962**, *54*, 464–465. [CrossRef]
36. Brady, N.C.; Weil, R.R. *The Nature and Properties of Soils*, 3rd ed.; Pearson Education Asia: Delhi, India, 2002; p. 960.
37. Walkley, A.J.; Black, I.A. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci.* **1934**, *37*, 29–38. [CrossRef]
38. Bhattacharyya, K.; Das, T.; Ray, K.; Dutta, S.; Majumdar, K.; Pari, A.; Banerjee, H. Yield of and nutrient–water use by maize exposed to moisture stress and K fertilizers in an inceptisol of West Bengal, India. *Agric. Water Manag.* **2018**, *206*, 31–41. [CrossRef]
39. Visconti, F.; De Paz, J.M.; Rubio, J.L. An empirical equation to calculate soil solution electrical conductivity at 25 C from major ion concentrations. *Eur. J. Soil Sci.* **2010**, *61*, 980–993. [CrossRef]
40. Kuehne, G.; Llewellyn, R.; Pannell, D.; Wilkinson, R.; Dolling, P.; Ouzman, J.; Ewing, M. Predicting farmer uptake of new agricultural practices: A tool for research, extension and policy. *Agric. Syst.* **2017**, *156*, 115–125. [CrossRef]
41. Gomez, K.A.; Gomez, A.A. *Statistical Procedures for Agricultural Research*; John Wiley & Sons: Hoboken, NJ, USA, 1984.
42. Goswami, R.; Roy, R.; Gangopadhyay, D.; Sen, P.; Roy, K.; Sarkar, S.; Misra, S.; Ray, K.; Monjardino, M.; Mainuddin, M. Understanding Resource Recycling and Land Management to Upscale Zero-Tillage Potato Cultivation in the Coastal Indian Sundarbans. *Land* **2024**, *13*, 108. [CrossRef]
43. Ramírez, D.A.; Silva-Díaz, C.; Ninanya, J.; Carbajal, M.; Rinza, J.; Kakraliya, S.K.; Gatto, M.; Kreuze, J. Potato zero-tillage and mulching is promising in achieving agronomic gain in Asia. *Agronomy* **2022**, *12*, 1494. [CrossRef]
44. Paul PL, C.; Bell, R.W.; Barrett-Lennard, E.G.; Kabir, E. Variation in the yield of sunflower (*Helianthus annuus* L.) due to differing tillage systems is associated with variation in solute potential of the soil solution in a salt-affected coastal region of the Ganges Delta. *Soil Tillage Res.* **2020**, *197*, 104489. [CrossRef]

45. Devi, S.; Gupta, C.; Jat, S.L.; Parmar, M.S. Crop residue recycling for economic and environmental sustainability: The case of India. *Open Agric.* **2017**, *2*, 486–494. [CrossRef]
46. Mondal, M.K.; Paul, P.; Humphreys, E.; Tuong, T.; Ritu, S.; Rashid, M.; Humphreys, E.; Buisson, M.; Pukinskis, I.; Phillips, M. Opportunities for cropping system intensification in the coastal zone of Bangladesh. In Proceedings of the CPWF, GBDC, WLE Conference on Revitalizing the Ganges Coastal Zone: Turning Science into Policy and Practices, Dhaka, Bangladesh, 21–23 October 2015; Humphreys, E., Tuong, T.P., Marie-Charlotte, B., Pukinskis, I., Phillips, M., Eds.; CGIAR Challenge Program on Water and Food (CPWF): Colombo, Sri Lanka, 2015; pp. 449–476.
47. Satapathy, B.S.; Singh, T.; Pun, K.B.; Saikia, K.; Rautaray, S.K. Influence of dates of planting and mulching on growth and tuber yield of potato (*Solanum tuberosum*) in rice (*Oryza sativa*) fallows of shallow lowland of Asom. *Indian J. Agron.* **2016**, *61*, 455–459. [CrossRef]
48. Sadawarti, M.J.; Singh, S.P.; Kumar, V.; Lal, S.S. Effect of mulching and irrigation scheduling on potato cultivar Kufri Chipsona-1 in Central India. *Potato J.* **2013**, *40*.
49. Sarkar, S.; Dey, S.; Dhar, A.; Banerjee, H. Boron nutrition in tuber crops: An inclusive insight. *Int. J. Veg. Sci.* **2024**, *30*, 470–496. [CrossRef]
50. Ramírez, D.A.; Hossain, M.M.; Rahaman, E.S.; Mestanza, C.; Rinza, J.; Ninanya, J.; de Mendiburu, F.; Loayza, H.; Gatto, M.; Kreuze, J.F. Potato production under zero tillage with rice straw mulching as a promissory technology to diversify rice-based systems in Southwest Coastal Bangladesh. *J. Agric. Food Res.* **2025**, *19*, 101603. [CrossRef]
51. Kumar, P.; Kumar, A.; Kumar, N.; Ahamad, A.; Verma, M.K. Effect of integrated nutrient management on productivity and nutrients availability of potato. *Int. J. Curr. Microbiol. Appl. Sci.* **2017**, *6*, 1429–1436. [CrossRef]
52. Mozumder, M.; Banerjee, H.; Ray, K.; Paul, T. Evaluation of potato (*Solanum tuberosum*) cultivars for productivity, nitrogen requirement and eco-friendly indices under different nitrogen levels. *Indian J. Agron.* **2014**, *59*, 327–335. [CrossRef]
53. Bhandari, S.; Bhandari, A.; Shrestha, J. Effect of different doses of triacontanol on growth and yield of kohlrabi (*Brassica oleracea* L. var. gongylodes). *Heliyon* **2021**, *7*. [CrossRef]
54. Qadri RW, K.; Khan, I.; Jahangir, M.M.; Ashraf, U.; Samin, G.; Anwer, A.; Bashir, M. Phosphorous and foliar applied nitrogen improved productivity and quality of potato. *Am. J. Plant Sci.* **2015**, *6*, 144–149. [CrossRef]
55. Mallick, S.; Ghosh, R.K.; Pal, D. Effect of triacontanol on the growth and yield of potato. *J. Crop Weed* **2009**, *5*, 154–156.
56. Dwivedi, S.K.; Kumar, A.; Pal, A.; Sriwastava, L.K.; Meshram, M. Effect of seaweed saps on growth, nutrient uptake and yield of potato (*Solanum tuberosum* L.). *Appl. Biol. Res.* **2016**, *18*, 1–7. [CrossRef]
57. Abd El-Mageed, T.A.; Semida, W.M.; Abd El-Wahed, M.H. Effect of mulching on plant water status, soil salinity and yield of squash under summer-fall deficit irrigation in salt affected soil. *Agric. Water Manag.* **2016**, *173*, 1–12. [CrossRef]
58. Bhanwaria, R.; Singh, B.; Musarella, C.M. Effect of organic manure and moisture regimes on soil physiochemical properties, microbial biomass Cmic: Nmic: Pmic turnover and yield of mustard grains in arid climate. *Plants* **2022**, *11*, 722. [CrossRef] [PubMed]
59. Mao, X.; Yang, Y.; Guan, P.; Geng, L.; Ma, L.; Di, H.; Liu, W.; Li, B. Remediation of organic amendments on soil salinization: Focusing on the relationship between soil salts and microbial communities. *Ecotoxicol. Environ. Saf.* **2022**, *239*, 113616. [CrossRef] [PubMed]
60. Fuglie, K.O. Conservation tillage and pesticide use in the cornbelt. *J. Agric. Appl. Econ.* **1999**, *31*, 133–147. [CrossRef]
61. Bader, C.; Stumpenhausen, J.; Bernhardt, H. Prediction of the Spatial and Temporal Adoption of an Energy Management System in Automated Dairy Cattle Barns in Bavaria-"CowEnergySystem. *Energies* **2024**, *17*, 435. [CrossRef]
62. Chandra, P.; Bhattacharjee, T.; Bhowmick, B. Does technology transfer training concern for agriculture output in India? A critical study on a lateritic zone in West Bengal. *J. Agribus. Dev. Emerg. Econ.* **2018**, *8*, 339–362. [CrossRef]
63. Varshney, D.; Joshi, P.K.; Kumar, A.; Mishra, A.K.; Dubey, S.K. Examining the transfer of knowledge and training to smallholders in India: Direct and spillover effects of agricultural advisory services in an emerging economy. *World Dev.* **2022**, *160*, 106067. [CrossRef]
64. Ojah, A.; Bhattacharjee, D. Zero tillage (ZT) potato cultivation. *Bhartiya Krishi Anusandhan Patrika* **2021**, *36*, 347–349. [CrossRef]
65. Sarangi, S.; Maji, B.; Digar, S.; Mahanta, K.K.; Sharma, P.C.; Mainuddin, M. Zero tillage potato cultivation is an innovative technology for coastal saline soils. *Indian Farming* **2018**, *68*, 23–26.
66. Parihar, C.; Singh, S.P.; Sharma, S.K.; Sadawarti, M.J.; Gupta, V.; Harsha; Chauhan, A.P.S.; Gupta, S.; Kumar, G. Effect of Zero Tillage Practices on the Economic Performance of Potato. *J. Exp. Agric. Int.* **2024**, *46*, 812–818. [CrossRef]

67. Chettri, P.; Goswami, S.B. Effect of crop and non crop mulch management under varying moisture regimes on the growth and yield of zero tillage potato in rain-fed low land rice eco system. *Int. J. Curr. Microbiol. Appl. Sci.* **2018**, *7*, 2334–2339. [CrossRef]
68. Saimon, A.H.; Mannan, M.A.; Sultana, S.; Mondal, A.R. Effect of straw and plastic mulches on growth and yield of zero tillage potato (*Solanum tuberosum* L.) in the Coastal Khulna Region of Bangladesh. *Int. J. Hortic. Sci.* **2024**, *30*, 23–30. [CrossRef]