agronomy

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Supplementing Nitrogen in Combination with Rhizobium Inoculation and Soil Mulch in Peanut (*Arachis hypogaea* L.) Production System: Part I. Effects on Productivity, Soil Moisture, and Nutrient Dynamics

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Received: 24 August 2020; Accepted: 10 October 2020; Published: 16 October 2020



Abstract: Peanuts (*Arachis hypogaea* L.) are the world's fourth-most important source of edible oil and the third-most valuable source of high-quality vegetable protein; they also contain carbohydrates, fatty acids, vitamins, and minerals essential for good human nutrition. Peanuts area particularly valuable crop in tropical and subtropical regions. While the demand for peanuts is increasing globally, there is a significant gap in nitrogen supply and demand in peanut production systems. To alleviate this, nitrogen fertilizers are often applied indiscriminately; this practice leads to the deterioration of indigenous soil fertility and to a long-term decline in crop productivity. Considering these aspects of soil health, a field study was conducted over two consecutive winter (November–March) seasons in 2015–2016 and 2016–2017 at the research farm of the agricultural university Bidhan Chandra Krishi Viswavidyalaya in West Bengal, India. This study examined supplementing different levels of nitrogen fertilizer with rhizobium and soil mulch in an irrigated peanut crop. The effects of these management interventions were evaluated in terms of crop productivity, nutrient dynamics, soil moisture, and the soil microbial activity. Peanuts grown with the 100% recommended dose of nitrogen, which was applied with rhizobium and grown under polythene mulching, recorded the highest average pod yield (3.87 and 3.96 t ha^{-1} in 2015–2016 and 2016–2017) and average kernel yield (2.88 and 2.99 t ha^{-1}) in both growing seasons. This treatment also resulted in the greatest accumulation of nitrogen, phosphorous, and potassium by the peanut plants. In contrast, the maximum soil moisture distribution and the greatest total root zone moisture content were observed in the treatment with only rhizobium under the polythene mulch (i.e., no nitrogen was applied). The populations of soil bacteria and rhizobia were highest in the treatment where nitrogen fertilizer was applied to the crop at 75% of the recommended rate combined with rhizobium and under polythene mulch. After two cropping seasons, the peanut

crop grown under polythene mulch with rhizobium and with nitrogen fertilizer applied at either the full recommended rate or 75% of this rate performed best in terms of crop productivity, soil nutrient dynamics, and soil moisture.

Keywords: biofertilizer; nitrogen dose; polythene mulch; quality traits; soil moisture

1. Introduction

Peanuts (*Arachis hypogaea* L.) are a key oilseed and food-legume crop for both humans and livestock in tropical and subtropical regions (i.e., between 40° N and 40° S). Peanuts comprise 44–56% edible oil; globally, they are the fourth largest source of edible oil. Additionally, peanuts contain 22–30% high-quality vegetable protein, 20% carbohydrates, as well as essential fatty acids, vitamins, and minerals necessary for human nutrition [1]. Peanuts are also a key source of earnings for small and marginal farmers in developing countries [2]. Peanuts are grown in 120 countries over a total area of 20.4 m-ha [3]. India has the greatest amount of land (4.99 m-ha) under peanut production, and is second, after China, in annual productivity terms (7.39 MT annually) [4]. Of the Indian peanut crop, 81% is processed for oil, 12% is retained as seed for future crops, 6% is consumed domestically, and about 1% is exported [5,6]. Growing peanuts in the winter (i.e., November to February) requires relatively high inputs (e.g., irrigation water) and thus increases production costs, but the yield of the crop grown at this time is almost double that grown during the rainy season (July to October). However, potential low-temperature stress during the early phase of peanut grown as a winter crop can be a significant obstacle to achieving substantial plant biomass and yield [7]. At the same time, peanuts extract a significant amount of nutrients from the soil, in particular soil nitrogen (N), during their growing season [8]. There is a significant gap between crop N uptake and the replenishment of soil N through the application of fertilizer. Increasing rates of N applied only exacerbates the depletion of soil health by increasing deficiencies in secondary and micronutrients [9], leading to the deterioration of indigenous soil fertility and the soil biological environment, and ultimately to the decline of the sustainable crop production system [10]. N is considered the most vital but limiting nutrient in any crop production system. It regulates plant growth and yield by influencing chlorophyll formation, enzymatic activities, and cell division and expansion [11]. N also indirectly influences seed oil production. However, an excessive application of inorganic N fertilizer inhibits the peanut nodule formation and thus the symbiotic N-fixing potential of the crop [12].

To overcome these challenges and continue to maintain or sustainably increase peanut productivity, improved and innovative management practices need to be identified for the improvement of peanut production and its oil quality. An earlier study reported that supplementing N fertilizer applications with microbial inoculants such as N-fixing biofertilizers, applied concurrently with the fertilizer, is a promising management option to maintain a balanced soil nutrient pool [13]. Symbiotic N fixation returns a significant amount of N from the atmosphere to soils through interactions between host plants and endo-symbionts [14]. Legume–Rhizobium (*Rh*) symbiosis is a well-known N_2-fixing plant–microorganism interaction, which has been used worldwide to promote plant growth [15]. The rhizobia *Bradyrhizobium japonicum* and *Bradyrhizobium elkaniiare* are the most reported nodulating root isolates for peanut cultivation [16]. Biological nitrogen fixation (BNF) through peanut–*Rh* symbiosis has been reported to provide up to 40.9 kg N ha^{-1} annually to a peanut crop [17]. The application of *Rh* inoculants also reduces mineral N loss by reducing the difference between peanut crop N demand and soil indigenous N supply [18]. Applying N fertilizer together with *Rh* not only assists in meeting peanut crop nutrient demand but also contributes to a sustainable crop productionsystem [8].

Plastic mulches are a useful management tool to manage soil temperature fluctuations [19], limit the direct loss throughthe evaporation of soil moisture, and control the weed seed bank [20]. Plastic mulching improves water infiltration within soils, increases plant water use efficiency and soil

water retention [21], decreases bulk density and soil erosion [22], and facilitates the condensation of soil water at night due to temperature reversals [23] and modification of the soil microclimate [24]. Mulching also alters microbial activity, retards the immobilization of N, and reduces N leaching, thereby facilitating better crop nutrient availability [25]. The application of plastic mulch is relatively inexpensive, and it is a management practice accessible to both smallholder subsistence farmers and those with larger farming operations.

There has been little previous work eitheron the effects of combining polythene mulch with different rates of N fertilizer or on applying *Rh* in irrigated peanut production. This research examined the individual and combined effects of these management options on peanut productivity and quality; soil moisture; and soil nutrient dynamics on peanut production in West Bengal, India. Peanut cultivation is emerging as a viable winter crop in West Bengal, and information must be available for farmers about the optimal management practices to sustainably increase peanut yields in this region. We evaluated the effect of *Bradyrhizobium* combined with different rates of inorganic N fertilizer under polythene mulching to assess the overall outcome on the agronomic sustainability of irrigated winter peanut production in terms of soil water, soil microbial populations, and peanut quality traits. The results observed here are applicable in other similar tropical agro-ecologies.

2. Materials and Methods

2.1. Site Characteristics

2.1.1. Location

The field experiment was conducted at the district seed farm of the agricultural university Bidhan Chandra Krishi Viswavidyalaya (BCKV), in Nadia, West Bengal, India (23°26′ N, 88°22′ E, elevation 12 m above mean sea level) during the winter (November to March) seasons of 2015–2016 and 2016–2017. One field was used for both experimental seasons; this field had not previously been used for peanut cultivation and had been fallow before the first experiment. Between the two peanut crops, a cereal crop was grown in the monsoon season.

2.1.2. Climatic Condition

The experimental site was in a subtropical climate characterized by hot and moderately humid summers (March–June),warm and humid rainy seasons (July–September), and dry and cold winters (October–February). Agro-meteorological observations during the experimental period were collected from the meteorological observatory station managed by the All India Coordinated Research Project on Agro-meteorology, BCKV, Kalyani, West Bengal, India. Maximum and minimum daily temperatures fluctuated from 38.6 to 11.8 °C and 34.3 to 10.9 °C in 2015–2016 and 2016–2017, respectively (Figure 1). A gradual drop of temperature was observed from November to January in both winter growing seasons. The maximum and minimum relative humidity of the experimental area range was 96–47.4% in 2015–2016 and 93.8–45.4% in 2016–2017 (Figure 1). The total rainfall during each experimental period (November–March) was 70.3 mm in 2015–2016 and 25.5 mm in 2016–2017. The greatest number of sunshine hours was observed in March and the smallest number was observed in December in both experimental seasons. Weather conditions were appropriate for the growth and development of a peanut crop during both experimental years.

2.1.3. Soil Characteristics

The soil of the experimental field was sandy loam in texture with 48% water-holding capacity (WHC) (*w*/*w*) and neutral pH. Before the experiment commenced, the soil was low in organic carbon and available N, and moderate in P and K (Table 1).

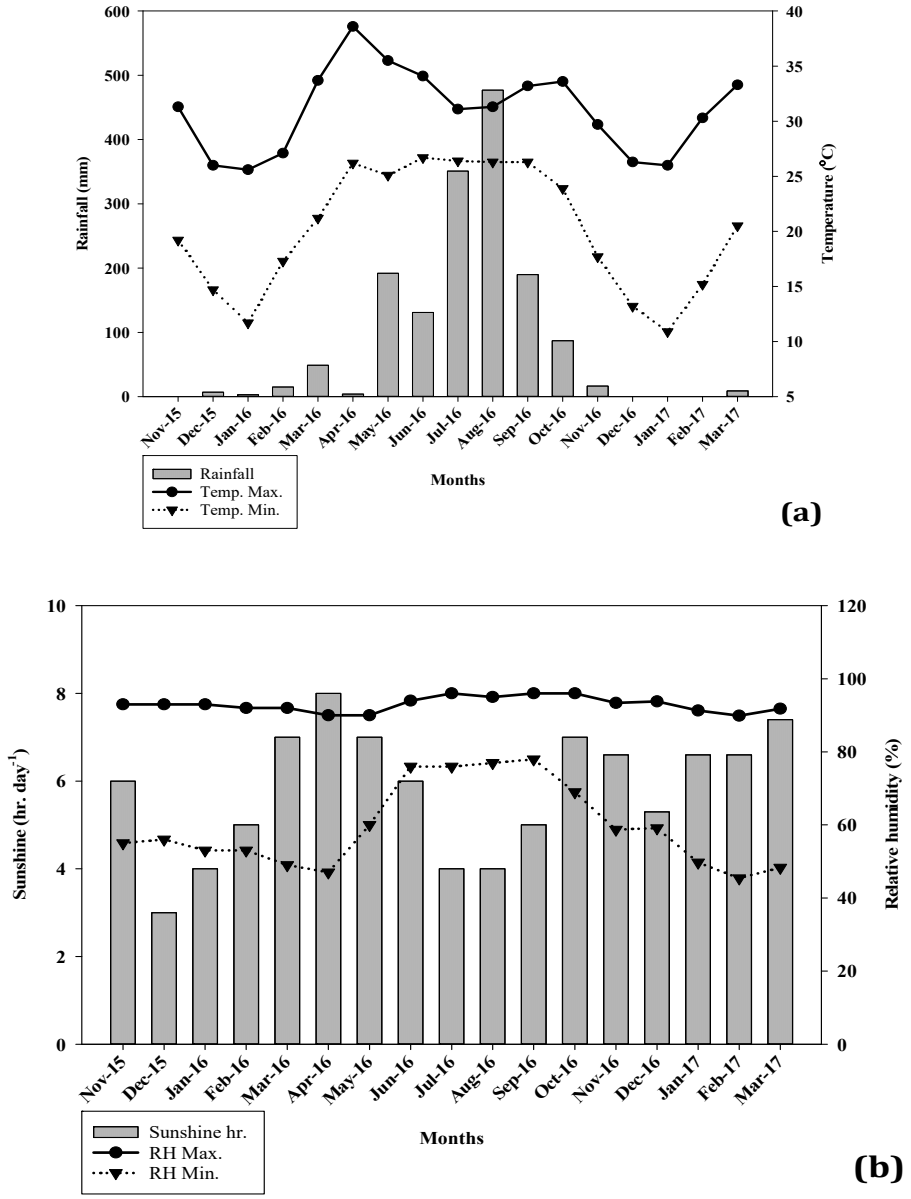


Figure 1. Monthly average rainfall and temperature (**a**), and sunshine hours and relative humidity (**b**) at the experimental site from winter 2015–2016 to winter 2016–2017.

Table 1. Physical and chemical properties of the soil in the study site in 2015–2016 and 2016–2017 at the onset of each experiment (0–30 cm depth).

Properties	Seasons		Analysis Methods
	2015–2016	2016–2017	
Physical properties			
Sand (%)	46.6	47.9	Hydrometer method [26]
Silt (%)	30.1	31.5	
Clay (%)	23.3	21.2	
Chemical properties			
pH	7.3	7.2	Glass electrode Beckman pH meter (in 1:2.5: Soil:Water) [26]
Organic Carbon (%)	0.53	0.50	Walkley and Black method [26]
Available N (kg ha^{-1})	195.3	213.7	Alkaline Permanganate method [26]
Available P (kg ha^{-1})	19.8	23.9	0.5 M $NaHCO_3$ extractable Olsen's Colorimetric method [26]
Available K (kg ha^{-1})	143.3	136.7	Flame photometric method [26]

2.2. Experimental Details

2.2.1. Design and Treatment Details

The experiment was laid out in a split-plot design with three replications. The main plots comprised two treatments: peanut grown under transparent 30µ polythene mulch and peanut grown with no mulching. There were seven sub-plot treatments: N fertilizer was applied at 50%, 75%, and 100% of the recommended dose of nitrogen (RDN) with or without *Rh*; in the seventh sub-plot treatment, *Rh* was applied without N. In the mulched treatments, immediately after seed sowing, a polythene sheet was spread over the entire bed with the edges buried in soil on both sides. After germination, small holes were made in the polythene to enable seedlings to emerge; these holes were retained until harvest. The main and sub-plots were replicated three times. Each sub-plot measured 3 m × 5 m; plots were at least 0.5 m apart.

2.2.2. Fertilizer Application

Recommended doses of phosphorus (P, as single super phosphate) and potassium (K, as muriate of potash) at 60 and 40 kg ha^{-1}, respectively, were applied basally in all treatments. N was applied in the prescribed treatments as urea (46% N). In the 100% of RDN treatment, the equivalent of 25 kg N ha^{-1} was applied to the experimental plot [1]; in the 75% treatment, the equivalent of 18.75 kg N ha^{-1} was applied, and in the 50% treatment, the equivalent of 12.50 kg N ha^{-1} was applied. The total amount of N was applied at basal immediately before sowing. Fertilizer was applied by hand uniformly across each experimental plot, following the best-practice recommendations of the Indian Council of Agricultural Research (ICAR). The recommended amounts of N, P, and K were selected based on recommendations from the ICAR-Directorate of Groundnut Research for the New Alluvial zone of West Bengal during the winter peanut season. The experimental treatments of 75% and 50% of the RDN were used to examine the trade-off between lowering the amount of chemical N applied to crops and farmers' desire to increase crop yield as far as practicable.

2.2.3. Variety and Experimental Setup

The peanut variety of TG51 was used in all experimental treatments. TG51 is a mutant derivative of TG26 × Chico, and it is an early-maturing (85–90 day), high-yielding variety developed by the Bhabha Atomic Research Centre, which is part of the Indian Department of Atomic Energy. The peanut seeds were manually sown at 150 kg ha^{-1} during the second fortnight of November in both 2015 and 2016, with 30 cm row-to-row distance and 10 cm seed-to-seed distance down each row. The seeds were mechanically sown: duck foot tines opened furrows into which seeds were placed at a depth of 3–4 cm; the soil was covered after seed placement. Before sowing, seeds were treated with mancozeb and carbendazim (SAAF) at 3 g kg^{-1} of seed kernel to avoid seed-borne diseases. Gypsum was applied in rows at the flowering stage, 5 cm away from plants to ensuring uniform pod setting and development, following best management practices provided by ICAR. The strain of *Rh* (*Bradyrhizobium japonicum*) was grown in 250 mL conical flasks containing 40 mL yeast-extract mannitol (YEM) broth in a shaking incubator for 3 days [27]. Cultures were shaken for eight hours each day at 28–30 °C. One millilitre (containing 108 cells) of the bacterial culture at their logarithmic stage of growth was used to inoculate surface-sterilized seeds which were then dried under shade for 30 minutes before sowing. Before the spreading of polythene mulch, fertilizers were applied in the polythene mulch plots.

Weeds were controlled with a pre-emergence application of pendimethalin 30% EC at 0.75 kg a.i. ha^{-1} at two days after sowing (DAS) followed by two hand weedings at 20 and 40 DAS (in the non mulched treatment plots). Chlorpyriphos 20 EC at 3 ml L^{-1} of water was sprayed at 35 and 50 DAS to deter sucking pests and defoliators.

2.2.4. Irrigation

One irrigation was applied, using a diesel-operated water-lifting pump, one week after sowing to facilitate crop establishment. Two more irrigations were applied at the critical crop-water-requirement stages, pegging and pod formation. All treatments received the same amount of irrigation water (i.e., were irrigated with a pipe of the same dimensions and for the same length of time).

2.2.5. Harvesting

Whole peanut plants were manually uprooted during the third week of March in both 2016 and 2017 and stacked (separated by treatment) in a clean, dry place for 5–7 days for sun-drying, following which pods were stripped manually from the plants and yield was recorded at 9–10% moisture. After shelling, the kernel yield was recorded using the same procedure. Haulm yield was recorded from the remaining plant biomass.

2.3. Measurements and Analytical Procedures

2.3.1. Yield Attributes and Yield

To determine yield attributes, five plants from the middle two rows in each plot were randomly selected at the time of maturity. These were harvested from each plot, dried, and the yield was recorded.

Post-harvest observations were recorded by counting and weighing pegs and pods from 10 randomly selected plants within each plot. These were converted into average numbers of pegs and pods per plant. The 100seed weight was obtained from a random sample of 100 seeds from each treatment and weighed by digital balance at 9–10% moisture after drying.

The sound mature kernel (SMK) ratio was calculated using the following Formula (1):

$$\text{SMK} = \frac{\text{Total weight of mature kernels}}{\text{Total weight of kernels}} \times 100 \quad (1)$$

where mature kernels were the kernels that had turned dark purple.

2.3.2. Microbiological Observations

The total soil microbial population was counted at sowing, 50 days after emergence (DAE) of the crop, and at harvesting to measure the microbial population development over the growing season. Soil samples were taken at five different points in each plot at a depth of 15 cm using a 5 cm diameter auger and bulked to 200–250 gm fresh weight. Colony-forming units (CFU) of bacteria and *Rh* were counted in nutrient agar and yeast extract manitol agar media, respectively, following serial dilution and the agar/pour plate method using a 1 mL soil solution for plating [28]. After incubation at 30 °C for three days, the populations of microbial bacteria and *Rh* were estimated from each plate [29].

2.3.3. Nutrient Assessment

Pre-sowing and post-harvest soil samples were taken from each experimental treatment at 0–30 cm depth to measure any changes in soil nutrient status. The hot alkaline permanganate method was used to estimate available soil N [28]. Available P was determined by UV–VIS spectrophotometer after soil extraction with 0.5 M $NaHCO_3$ (pH 8.5) [28]. The available K in soil was determined using neutral (N) ammonium acetate as an extracting reagent and estimated by a flame photometer [28].

Plant samples were collected from each treatment, dried at 60 ± 5 °C in a hot air oven, ground, and sieved through 0.5 mm mesh sieve to determine the recoveries of N, P, and K at harvest. Nitrogen was determined by the micro-Kjeldahl method. For P and K, plant samples were digested in a tri-acid (HNO_3:H_2SO_4:$HClO_4$ = 10:1:4) mixture, followed by recovery estimation with a spectrophotometer or flame photometer, respectively [28]. A nutrient balance sheet was prepared based on the method specified by [1].

2.3.4. Quality Assessment

Protein and oil content in peanut kernels were determined using a near-infrared analyzer. The oil yield and protein yield were calculated by multiplying the kernel yield with oil content or protein content, respectively.

2.3.5. Determination of Soil Moisture Content

Soil samples were collected from each plot using a 5 cm diameter auger at 0–15, 15–30, and 30–45 cm depths and weighed in a digital weighing machine. Soil samples were dried in a hot air oven at 105 °C temperature for 24–48 h to obtain a constant weight; then, the weight of the dry soil samples was recorded. The gravimetric moisture content was obtained using the following Formula (2):

$$\text{Moisture content (Weight basis)} = \frac{\text{Wet weight} - \text{Dry weight}}{\text{Dry weight}} \times 100. \quad (2)$$

Volumetric water content was calculated by multiplying the gravimetric moisture content with the soil bulk density. The root zone moisture content at the different depths was calculated by multiplying the volumetric moisture content by the respective soil depth.

2.3.6. Statistical Analysis

The data obtained from the experiment were subjected to Analysis of Variance (ANOVA) using the STAR (Statistical Tool for Agricultural Research) [30]. Significantly different means were separated at the 0.05% or 0.01% probability level using Duncan's Multiple Range Test.

3. Results and Discussion

3.1. Yield-Attributing Characteristics of Peanut were Influenced by Levels of Nitrogen Applied with Rh under Mulch

The effect of the treatment combinations on yield-attributing traits such as pegs per plant, pods per plant, percentage of sound mature kernels, and test weight are summarized in Table 2; significance was determined at $p \leq 0.05$. The highest number of pegs per plant (31.40) in the first season was observed in the treatment where fertilizer applied at 75% of the recommended dose of N (RDN) was combined with *Rh* under polythene mulching; this was similar to the number of pegs per plant in the treatments where 100% RDN was applied with or without *Rh* under both mulching and non-mulching and where 75% RDN was applied under mulching. In the second season, the highest number of pegs per plant(31.30) was observed in the 100% RDN treatment with *Rh* and mulching. Similar results were observed in terms of the number of pods observed per plant: the treatment with 100% RDN combined with *Rh* under mulching recorded the highest number of pods per plant(30.57), while the treatment with only *Rh* with no N or mulching recorded the lowest number of pods per plant. These findings are similar to those of Negi et al. [31], who observed that supplementing starter dose of mineral N with a N-fixing biofertilizer resulted in maximum pod load in legume crops.

Favourable moisture content under poly-mulching during pegging and pod development lowers the soil mechanical resistance [32]; this may be a reason for the observed maximum peg and pod numbers in our experiment, which are also in line with those reported by Khan [33]. Namvar et al. [34] investigated the effect of different N doses with or without *Rh* inoculation on the growth and yield of chickpea and reported a 16.19% increase in the number of pods per plant in the treatment that received the maximum dose of N combined with biofertilizer inoculation, compared to the control treatment. Our result also agrees with that of Caliskan et al. [35], while Togay et al. [36] also concluded that *Rh* inoculation has a significant influence on the number of pods per plant; they observed an average of 12.35 pods plant^{-1} from *Rh*-inoculated plants compared to an average of 11.50 pods plant^{-1} from non-inoculated control plants.

Table 2. Yield attributing traits of peanut under different mulching and nutrient management practices.

Treatment Details	Peg Plant^{-1}		Pod Plant^{-1}		SMK (%)		100 Kernel Weight (g)	
	2015–2016	2016–2017	2015–2016	2016–2017	2015–2016	2016–2017	2015–2016	2016–2017
Mulching								
100% RDN	29.30 ^{abc}	29.90 ^{abcd}	24.60 ^{abc}	25.20 ^{bc}	93.30 ^{ab}	92.50 ^{ab}	45.50 ^{ab}	46.00 ^{ab}
75% RDN	30.40 ^{ab}	31.20 ^{ab}	23.30 ^{bc}	23.75^{cd}	91.70 ^{ab}	91.60 ^{ab}	44.90 ^{abc}	45.30 ^{abcd}
50% RDN	27.40 ^{c}	29.40 ^{bcd}	19.00 ^{ef}	19.42 ^{fg}	88.40 ^{b}	90.20 ^{bc}	43.30 ^{c}	44.80 ^{abcd}
100% RDN + *Rh*	30.10 ^{ab}	31.30 ^{ab}	25.20 ^{ab}	30.57 ^{ab}	94.20 ^{ab}	93.50 ^{ab}	46.10 ^{ab}	45.90 ^{abc}
75% RDN + *Rh*	31.40 ^{ab}	30.90 ^{abc}	25.90 ^{ab}	25.40 ^{bc}	93.30 ^{ab}	93.10 ^{ab}	45.90 ^{ab}	46.30 ^{ab}
50% RDN + *Rh*	28.20 ^{bc}	28.60^{cd}	20.90 ^{de}	21.10 ^{ef}	88.70 ^{b}	89.90 ^{bc}	44.80 ^{abc}	45.20 ^{abcd}
Rhizobium (*Rh*)	22.21 ^{d}	21.90 ^{f}	13.20 ^{g}	14.93 ^{h}	82.70 ^{de}	83.60 ^{f}	44.20 ^{abc}	43.70 ^{d}
Non-mulching								
100% RDN	27.21 ^{c}	27.90 ^{de}	20.50 ^{de}	22.94 ^{de}	87.60 ^{bc}	88.10 ^{cde}	44.60 ^{abc}	45.10 ^{abcd}
75% RDN	26.82 ^{c}	27.70 ^{de}	19.60 ^{ef}	20.30 ^{fg}	86.90 ^{bc}	87.30^{de}	43.30 ^{bc}	44.30 ^{abcd}
50% RDN	24.30 ^{d}	23.20 ^{f}	17.80 ^{f}	16.70 ^{h}	83.60 ^{de}	88.20 ^{cde}	43.00 ^{c}	44.00 ^{bcd}
100% RDN + *Rh*	29.24 ^{abc}	28.90 ^{bcd}	22.30 ^{cd}	26.64 ^{b}	88.60 ^{b}	89.00 ^{cd}	45.00 ^{abc}	45.30 ^{abcd}
75% RDN + *Rh*	28.30 ^{bc}	29.10 ^{bcd}	20.80 ^{de}	23.69 ^{cd}	87.20 ^{bc}	88.00 ^{cde}	44.60 ^{abc}	44.80 ^{abcd}
50% RDN + *Rh*	27.90 ^{bc}	26.00 ^{e}	18.70 ^{ef}	18.95 ^{g}	85.00 ^{cd}	86.30 ^{e}	43.30 ^{c}	43.80 ^{cd}
Rhizobium (*Rh*)	24.00 ^{d}	21.90 ^{f}	11.40 ^{g}	10.20 ^{i}	81.90 ^{e}	82.90 ^{f}	43.00 ^{c}	43.70 ^{d}
F-test								
Mulching (M)	**	**	**	**	**	*	*	*
Nitrogen (N)	**	**	*	**	*	*	**	**
M × N	*	*	*	*	**	**	*	**

RDN, recommended dose of N: 100% = 25 kg ha^{-1}; within column numbers followed by different letters indicate significant differences at $p \leq 0.05$ (otherwise statistically at par); ns: non-significant ($p > 0.05$); ** Significant at $p \leq 0.01$; * Significant at $p \leq 0.05$.

The percentage of sound mature kernels (SMKs) indicates the number of kernels that matured compared to the total number of kernels produced by a plant: this varied significantly with mulching ($p \leq 0.01$), N dose ($p \leq 0.05$), and their interaction effect ($p \leq 0.01$) (Table 2). High SMK (94.20%) was observed in the first season from the treatment that combined mulching with 100% RDN and *Rh*; this was statistically equivalent to treatments without added biofertilizer and with 75% RDN, irrespective of *Rh* supply. The lowest SMK (81.90%) was observed in the treatment with sole *Rh* inoculation without mulching or fertilizer N. In the second season, a similar trend in observations was recorded.

The maximum weight of a hundred kernels (46.10 g) was recorded in the treatment with the highest N dose with *Rh* and mulching in 2015–2016 (Table 2). In 2016–2017, the treatment with 75% RDN with *Rh* resulted in a 100-kernel weight of 46.30 g; this was statistically greater than treatments with 50% RDN applied with or without *Rh* under non-mulched conditions than the treatment that had no N fertilizer. An increase in seed weight with increasing levels of applied N was also reported by Nalayini et al. [37] and Hamaguchi et al. [38].

Mulching positively influenced the number of pods, the 100-kernel weight, and the pod yield [6]. A higher pod load (i.e. number of pods per plant) was observed in treatments when the seed had been inoculated with *Rh* than in non-inoculated peanut-seed treatments [39]. Jain et al. [7] reported a 37.60 g 100-kernel weight under polythene mulching compared to a 35.8 g 100-kernel weight under traditional practice. Under mulched treatments, the soil was not disturbed throughout the growing season; this has the potential to improve the soil physical health by keeping soil crusting low and maintaining soil bulk density. In contrast, rainwater impact and runoff may have increased soil crusting in the non-mulched plots. Additionally, soil disturbance during weeding and earthing-up operations may have increased the bulk density in the uncovered soil. A favourable soil structure under mulch has been shown to improve total soil porosity, soil capillary porosity, and soil aeration porosity [40], and it may have contributed to improved pegging and pod formation.

Hasan and Sahid [41] established that inoculating peanut seed with *Rh* improved the number of pods per plant, the 100-seed weight, and the shelling percentage. Jain et al. [7] also observed that combining mulching with the maximum recommended dose of N resulted in better yield-attribution traits in peanuts.

3.2. Peanut Yield Was Influenced by Different Levels of Nitrogen Fertilizer in Association with Rh and Mulch

The yield traits of peanut, in terms of pod yield, kernel yield, and haulm yield, were significantly influenced by mulching and nutrient management practices (Table 3). The highest pod yield (3.87 t ha^{-1}) in the 2015–2016 growing season was observed in the treatment where peanut was grown under polythene mulch, which was fertilized with the full recommended N dose and with *Rh* supplementation; this pod yield was statistically similar to that observed in the treatment with 75% RDN with *Rh* inoculation under mulching. These yields were 29% higher than that observed in the treatment that received 100% RDN with no mulching or *Rh*, and they were 178% higher than the control treatment (i.e., *Rh* applied without mulching or N fertilizer). In the second season, treatments with mulching had significantly ($p \leq 0.01$) higher pod yields (an average of 3.04 t ha^{-1}) than those with no mulching. Jain et al. [1] also reported 35.55% higher pod yields under mulch than under non-mulched treatments. Ravankar et al. [42] reported that treatments with 100% RDN (i.e., 25 kg ha^{-1}) produced higher yields (3.75 t ha^{-1}) than treatments with lower N applications. Better pod yield may be attributed to superior growth responses and yield-determining factors with the supply of higher N doses, which was also observed by Namvar et al. [34].

Consistent with the results observed for pod yield, the productivity of the peanut kernel was recorded the maximum (2.88 and 2.99 t ha^{-1} in the first and second seasons) in the treatments where 100% of RDN was applied with *Rh* and under mulching. These yields differed significantly from all other treatments in both experimental years except for the application of 100% of RDN without *Rh* under mulching in the second season (Table 3), which were 216.48% and 247.67% higher, respectively, than the control treatment. Similarly for peanut haulm, the highest yield of 4.62 t ha^{-1} was achieved in the treatment combining mulching with 100% RDN and *Rh* in the first season. However, in the second season, no statistical differences were observed between treatments. Our results are consistent with those of Ravankar et al. [42] and Shaikh et al. [43], who additionally concluded that peanut cultivated under mulching yielded 7% more haulm than an unmulched control treatment. Plastic mulch traps the longer wavelength radiation emitting from the soil, which enhances the soil temperature, inhibits weed germination, and promotes a more favorable soil temperature [44]. This improved microclimate also contributes to better plant stands, leading to greater crop yields.

Table 3. Yield and quality of peanut under different mulching and nutrient management practices.

Treatments	Pod Yield (t ha^{-1})		Kernel Yield (t ha^{-1})		Haulm Yield (t ha^{-1})		Oil Yield (t ha^{-1})		Protein Yield (t ha^{-1})	
	2015–2016	2016–2017	2015–2016	2016–2017	2015–2016	2016–2017	2015–2016	2016–2017	2015–2016	2016–2017
Mulching										
100% RDN	3.65 ^{b}	3.83 ^{ab}	2.58 ^{bc}	2.80 ^{ab}	4.36 ^{bc}	4.47 ^{ab}	1.21 ^{b}	1.35 ^{b}	0.66 ^{b}	0.71 ^{b}
75% RDN	3.49 ^{bc}	3.60 ^{ab}	2.45 ^{cd}	2.50 ^{cde}	4.18 ^{cd}	4.24 ^{ab}	1.10 ^{c}	1.15 ^{cd}	0.60 ^{c}	0.62 ^{cd}
50% RDN	3.32 ^{c}	3.46 ^{ab}	2.31 ^{de}	2.38 ^{def}	4.02 ^{d}	4.11 ^{ab}	0.97 ^{ef}	1.02 ^{ef}	0.54 ^{de}	0.56 ^{efg}
100% RDN + *Rh*	3.87 ^{ab}	3.96 ^{ab}	2.88 ^{ab}	2.99 ^{ab}	4.62 ^{ab}	4.58 ^{ab}	1.38 ^{ab}	1.46 ^{ab}	0.75 ^{ab}	0.78 ^{ab}
75% RDN + *Rh*	3.70 ^{ab}	3.75 ^{ab}	2.63 ^{b}	2.62 ^{bc}	4.47 ^{ab}	4.41 ^{ab}	1.20 ^{b}	1.22 ^{c}	0.66 ^{b}	0.65 ^{c}
50% RDN + *Rh*	3.56 ^{b}	3.62 ^{ab}	2.49 ^{bc}	2.53 ^{cd}	4.29 ^{bc}	4.27 ^{ab}	1.06 ^{d}	1.09 ^{de}	0.60 ^{c}	0.60^{def}
Rhizobium (*Rh*)	1.68 ^{h}	1.59 ^{ab}	1.14 ^{j}	1.08 ^{j}	2.22 ^{i}	2.12 ^{ab}	0.44 ^{j}	0.42 ^{h}	0.24 ^{i}	0.23 ^{j}
Without mulching										
100% RDN	3.00 ^{de}	3.20 ^{ab}	2.09 ^{fg}	2.22 ^{fgh}	3.67 ^{ef}	3.90 ^{ab}	0.98 ^{def}	1.07 ^{de}	0.54 ^{de}	0.57 ^{defg}
75% RDN	2.84 ^{efg}	3.05 ^{ab}	1.96 ^{ghi}	2.11 ^{ghi}	3.48 ^{fgh}	3.72 ^{ab}	0.88 ^{gh}	0.97 ^{f}	0.49 ^{fg}	0.52 ^{gh}
50% RDN	2.68 ^{g}	2.88 ^{ab}	1.82 ^{i}	1.92 ^{i}	3.31 ^{h}	3.65 ^{ab}	0.77 ^{i}	0.83 ^{g}	0.43 ^{h}	0.45 ^{i}
100% RDN + *Rh*	3.11 ^{d}	3.29 ^{ab}	2.18 ^{ef}	2.30 ^{efg}	3.77 ^{e}	3.93 ^{ab}	1.04 ^{cde}	1.13 ^{cd}	0.57 ^{cd}	0.61 ^{cde}
75% RDN + *Rh*	2.94 ^{def}	3.17 ^{ab}	2.07 ^{fgh}	2.20 ^{fgh}	3.60 ^{efg}	3.90 ^{ab}	0.94 ^{fg}	1.03 ^{ef}	0.52 ^{ef}	0.55 ^{fg}
50% RDN + *Rh*	2.77 ^{fg}	2.90 ^{ab}	1.91 ^{hi}	2.01 ^{hi}	3.43 ^{gh}	3.69 ^{ab}	0.81 ^{hi}	0.88 ^{g}	0.46 ^{gh}	0.48 ^{hi}
Rhizobium (*Rh*)	1.39 ^{i}	1.29 ^{ab}	0.91 ^{k}	0.86 ^{k}	1.90 ^{j}	1.87 ^{ab}	0.35 ^{k}	0.34 ^{h}	0.19 ^{j}	0.19 ^{j}
F-test										
Mulching (M)	**	**	**	**	**	**	**	*	*	**
Nitrogen (N)	**	**	**	**	**	**	**	*	**	**
M × N	*	ns	*	*	**	ns	**	*	*	*

RDN, recommended dose of nitrogen: 100% = 25 kg ha^{-1}; within column numbers followed by different letters indicate significant differences at $p \leq 0.05$ (otherwise statistically at par); ns: non-significant ($p > 0.05$); ** Significant at $p \leq 0.01$; * Significant at $p \leq 0.05$.

Additionally, the usage of biofertilizers may enhance agronomic output. Asante et al. [39] observed that peanut seeds inoculated with *Rh* had 13–40% higher yields than treatments without inoculation. Argaw [45] concluded that while the application of *Bradyrhizobium* alone did not improve the kernel yield of peanut, interactions between mineral N fertilizer and *Rh* did increase kernel yield. Namvar et al. [34] found that the interaction of *Rh* with higher N rates increased kernel and haulm yield compared to plants with the same rate of N fertilization but without *Rh* inoculation. Ghosh et al. [6] observed 20% higher peanut yields from the interaction of mulching with a high N dose (25 kg ha^{-1}) compared to a control treatment. They suggested that the favorable microclimate combined with an optimum supply of plant nutrients facilitated better growth, yield-determining traits, and ultimately peanut yield.

The amount of oil and protein obtained from peanut kernels was significantly ($p \leq 0.01$) influenced by mulching and nutrient dose, as summarized in Table 3. The treatment with mulch and 100% RDN with *Rh* resulted in the highest oil yield in both seasons (1.38 and 1.46 t ha^{-1}), while the lowest oil yields (0.44 and 0.42 t ha^{-1}) were observed in the non-mulched plot where *Rh* was applied in the absence of N. The highest protein yield was observed from the treatment that received 100% RDN with *Rh* (0.78 t ha^{-1}) under mulching, followed by that from the treatment with 100% RDN under mulching but without *Rh* (0.71 t ha^{-1}). These findings are comparable to those observed by Singh et al. [46]. Oil and protein yield are a function of their concentration within the kernel and of the kernel yield. Jain et al. [1] reported a 1.31-fold higher protein yield and 1.20% higher oil content from peanut kernels under mulch compared to those without mulch. Hasan and Sahid [41] reported that the seed inoculation of *Rh* resulted in higher oil (54.30%) and protein (25.60%) content than was achieved from non-inoculated plants. Jain et al. [7] also reported that peanut fertilized with 100% RDN under mulching resulted in greater pod yield, kernel yield, oil yield, and protein yield than other treatments.

Sharma et al. [47] observed protein concentrations of 24.90% under 100% RDN and of 21.90% from the control (0% N) plot. They also reported 24.10% and 10.70% higher oil content and oil yield, respectively, from the 100% RDN treatment than from the control treatment. Rathore and Kamble [48] suggested that while there is no direct relationship between peanut plant N content and oil yield, N may indirectly influence the synthesis of essential metabolites responsible for higher oil content and oil yield. Sarr et al. [49] found that a combination of fertilizer interventions in legume cropping systems including organic soil amendments, legume-specific fertilizer, and *Rh* inoculants were more efficacious in increasing crop yield, oil content, and protein content than the application of N fertilizer alone.

3.3. Supplementation of Different Levels of Nitrogen in Association with Rh and Soil Mulch Influence the Soil Bacterial Populations at Different Growth Stages of Peanut

The soil microbial population was affected by mulching. The total bacterial population did not significantly differ between the soil samples collected from the mulched and non-mulched plots before sowing irrespective of the year (Figure 2a,b). The total bacterial population was highest at harvesting under the mulch treatments in both 2015–2016 and 2016–2017 (58.20 and 64.76 CFU $\times 10^4$ g^{-1}, respectively); this was significantly ($p \leq 0.01$) higher than the bacterial populations observed in the non-mulched plots. These findings are similar to those of Subrahmaniyan et al. [40], who reported that mulch improved bacterial populations at different crop growth stages. Higher microbial populations were significantly correlated with soil moisture content. We observed higher soil moisture under mulch, which may have increased micro-flora populations. Farmer et al. [50] observed an increasing trend in bacterial populations under mulch over the long-term (28 years) experiment.

In the first season, the treatment with 100% RDN in combination with *Rh* resulted in the highest bacterial population (47.60 CFU $\times 10^4$ g^{-1}) in the soil at 50 DAE, while the treatment with 75% RDN with *Rh* had the highest bacterial population (61.42 CFU $\times 10^4$ g^{-1}) during harvesting. These results were statistically equivalent to those observed under the high-dose treatments (i.e.,100% RDN with or without *Rh*) in the subsequent growing season (60.27 CFU $\times 10^4$ g^{-1} and 58.90 CFU $\times 10^4$ g^{-1}, respectively) (Figure 2c). Al-Kaisi et al. [51] observed that increasing the rate of N fertilization did not always significantly influence the rhizospheric micro-flora. However, in the second season,

the bacterial population was significantly influenced by nutrient doses (Figure 2d). Initially (at sowing), the population was higher in the 100% RDN with *Rh* treatment (39.30 CFU × 10^4 g^{-1}), but at later observations (i.e., 50 DAE and harvest), the highest population was recorded from the treatment that received 100% RDN and no *Rh* (54.25 and 67.70 CFU × 10^4 g^{-1}, respectively). Wang et al. [52] observed that without mulch, N-fertilizer alone may increase soil microbial biomass significantly. Liu et al. [53] also reported that the application of different rates of N fertilizer significantly influences soil microbial populations over the longer term.

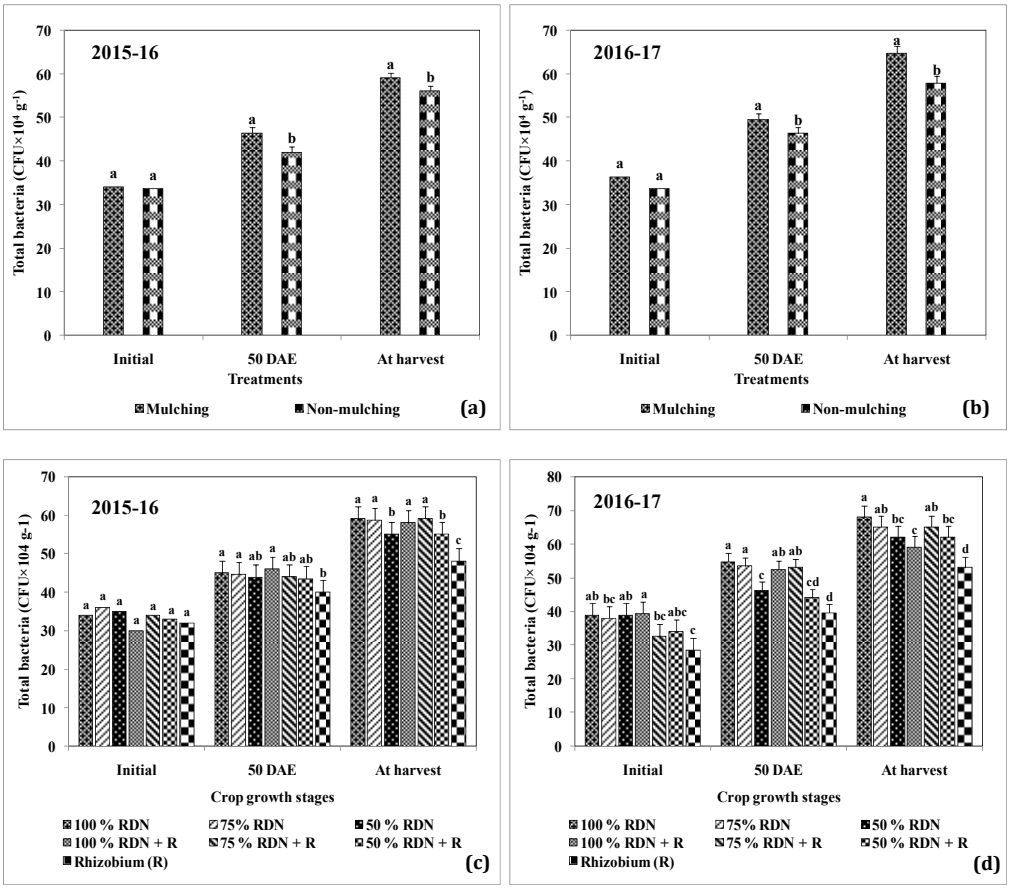


Figure 2. Effect of mulching (**a**,**b**) and nutrient doses (**c**,**d**) on soil bacterial populations at different growth stages of peanut (data from the 2015–2016 and 2016–2017 crop seasons, respectively); DAE—Days after emergence; within treatments, different letters indicate significant differences at $p \leq 0.05$ (otherwise statistically at par); error bars represent the least significant difference value.

Treatments with mulch resulted in significantly higher *Rh* populations than those without mulch at harvesting in both seasons (Figure 3a,b). The observed *Rh* population did not vary significantly with different doses of N fertilizer at the initial observation; however, at harvest, the microbial population had significantly increased in the treatment with 75% RDN with *Rh* (38.30 and 34.70 CFU × 10^4 g^{-1} in the first and second seasons, respectively).

There were no statistically significant differences in the soil *Rh* population between the initial and harvesting in treatments of varying nutrient doses, except that the treatment with no N application had a lower *Rh* population than in all other treatments. Hu et al. [54] reported that mulch increased N-fixing bacteria by 47.30% compared to non-mulched treatments in peanut experiments. The favourable microclimate under mulch is assumed to stimulate root growth and increase root exudation [25,40], resulting in improved nutrient supply to soil microorganisms [55]. This may explain the greater observations of *Rh* and other bacterial populations in our study. In a long-term field experiment, researchers showed that the interaction between mulch and N fertilization significantly improved

microbial biomass and microbial activity, as a result of higher soil carbon and soil water availability for microbes [56]. Tiquia et al. [57] also reported that the total microbial biomass was significantly higher after mulch combined with fertilizer. However, the population of soil microbes varies considerably with mulching material and composition as well as the source of N fertilizer [58].

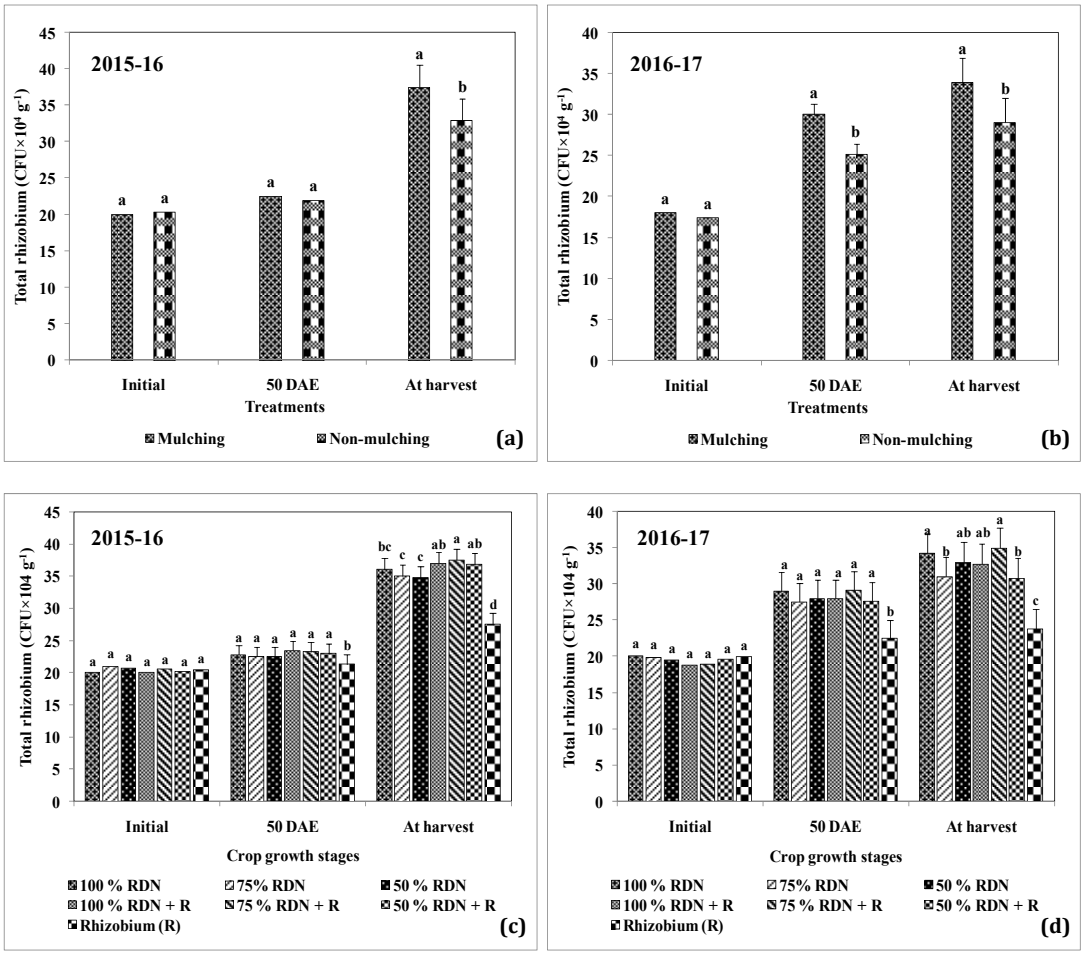


Figure 3. Effect of mulch (**a**,**b**) and nutrient dose (**c**,**d**) on soil *Rh* populations at different growth stages of peanut (data from 2015–2016 and 2016–2017 crop seasons respectively); DAE—days after emergence; within treatments, different letters indicate significant differences at $p \leq 0.05$ (otherwise statistically at par); error bars represent the least significant difference value.

3.4. Soil Moisture Status and Distribution are Influenced by Different Levels of Nitrogen Fertilizer Applied with Rh and Soil Mulch

Soil moisture at the peanut pegging stage increased with depth from 0 to 450 mm (Figure 4). Mulch significantly influenced the soil moisture content between 0 and 300 mm. In the first experimental season, at 0–150 mm depth, moisture was 26.14% higher under mulch than in non-mulched treatments; at 150–300 mm depth, the soil moisture under mulch was 11.49% higher, and at 300–450 mm, there was no statistically significant difference in soil moisture between mulched and non-mulched treatments (Figure 4a). As a result, higher moisture storage (12.27 cm) was observed in the root zone under mulched than under non-mulched (10.99 cm) treatments (Figure 5a). The difference in moisture storage reduced significantly with increasing soil depth. A similar trend was observed in root zone moisture storage in 2016–2017, as presented in Figure 5b.

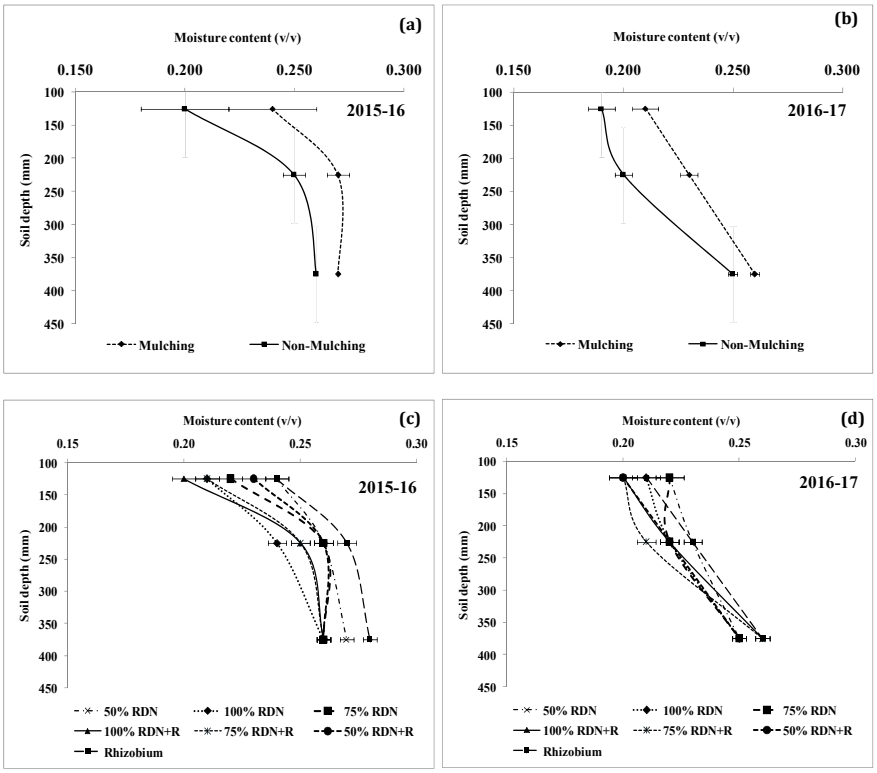


Figure 4. Effect of mulch (**a**,**b**) and nutrient dose (**c**,**d**) on soil moisture content (*v*/*v*) at pegging stage of peanut (data of 2015–2016 and 2016–2017 crop seasons, respectively); error bars represent the least significant difference value.

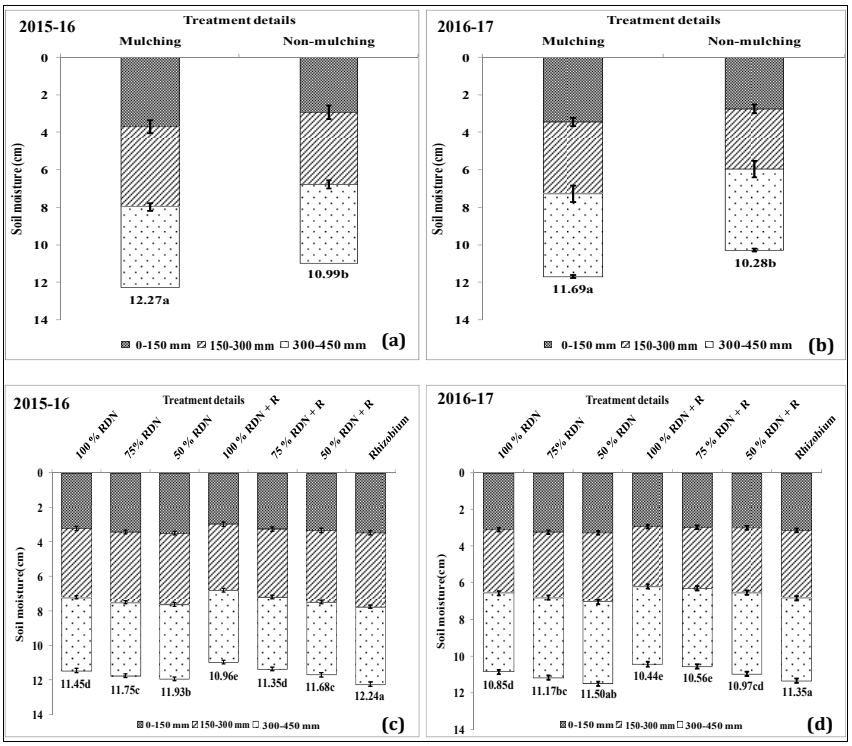


Figure 5. Effect of mulch (**a**,**b**)and nutrient dose (**c**,**d**) on root zone moisture storage (cm) at the pegging stage of peanut (data from 2015–2016 and 2016–2017 crop seasons, respectively); within treatments numbers followed by different letters indicate significant differences at $p \leq 0.05$ (otherwise statistically at par); error bars represent the least significant difference value.

These results are consistent with [7] who reported that mulch consistently improved soil moisture storage throughout the peanut growing season. Overall, the more harvestable product was achieved in mulched plots than non-mulched plots, and harvest indices were significantly higher under mulching than without mulching for both experimental years (data are shown in the companion paper, published in 'Agronomy') [59]. Thus, peanut in mulched treatments had a higher conversion of water into harvestable yield than in non-mulched treatments.

Soil moisture content (*v*/*v*) varied between 19.50% and 30.21% under different nutrient management practices across the whole 0–450 mm soil profile (Figure 4c,d). In the topsoil, the highest soil moisture (23.31%) was observed in the treatment with 50% RDN with no *Rh* supplementation, followed by the treatment with only *Rh* supplementation. The smallest top soil moisture was observed in the treatment with 100% RDN with *Rh* supplementation (Figure 4c). However, at depth, higher residual soil moisture (28.54%) was observed only in the treatment with *Rh* supplementation alone. Similarly, in the 300–450 mm layer, low soil moisture (27.8%) was observed in the treatment with 75% RDN with *Rh*; this was statistically similar to the treatment with 100% RDN with *Rh*. Figure 5c,d illustrates that at the pegging stage, a small amount of total root zone moisture was present (11.13 and 11.65 cm, respectively, in the first and second seasons) in the treatment with 100% RDN with *Rh*: this may be due to higher evapotranspiration losses associated with increased biomass resulting from higher N application. Soil moisture content was strongly related to received precipitation and crop evapotranspiration [60].

The soil moisture distribution and the root zone moisture storage during peanut pod formation are illustrated in Figures 6 and 7. The treatments grown under mulch had higher soil moisture contents, particularly at 0–150 mm depth. A similar trend in soil moisture storage was observed by Gao et al. [61]. In 2015–2016, soil moisture under the non-mulched treatments increased from 14.16% to 20.96% from the upper to the middle depths, while in the mulched treatments, a slower rate of increasing soil moisture was observed (Figure 6a). These findings indicate higher evaporative loss from the uncovered soil surface. The covering effect was not prominent at lower soil depths or in the second season; the moisture content at 300–450 mm was not significantly different between mulched and non-mulched treatments. A similar finding was observed inthe case of root zone moisture storage: 9.86 cm moisture under mulch and 8.61 cm moisture under non-mulched treatments (Figure 7a). Reductions in evaporation and weed populations under the mulch may explain the higher soil moisture storage under mulch [1]. Mulumba and Lal [62] also observed higher soil moisture retention (29–70%) and available soil water capacity (18–35%) in mulched conditions compared to non-mulched treatments. The treatment fertilized with 50% RDN without biofertilizer resulted in a higher amount (19.76%) of soil moisture in the upper root zone, which was closely followed by the same treatment with *Rh* (Figure 6c). In contrast, the treatment with 100% RDN with *Rh* had the lowest soil moisture content in both experimental seasons. Root zone moisture storage is a consequence of soil moisture content. The results obtained from Figure 7c,d illustrate that root zone moisture storage was higher in treatments with lower doses of fertilizer.

In the first experimental season, the maximum residual soil water storage (10.24 cm) was observed in the treatment with 50% RDN (Figure 7c), while the minimum soil moisture storage (7.97 cm) was observed in the treatment with 100% RDN with *Rh*. A similar trend was observed in the subsequent season (Figure 7d). The healthy and vigorous plant growth facilitated by the application of N fertilizer is likely to increase crop water demand and thus result in lower soil moisture in the higher N fertilizer treatments regardless of the presence of mulch. The soil moisture at earlier crop growth stages primarily depended on topsoil evaporation, but from the reproductive stage onwards, soil moisture varied with crop evapotranspiration [63].

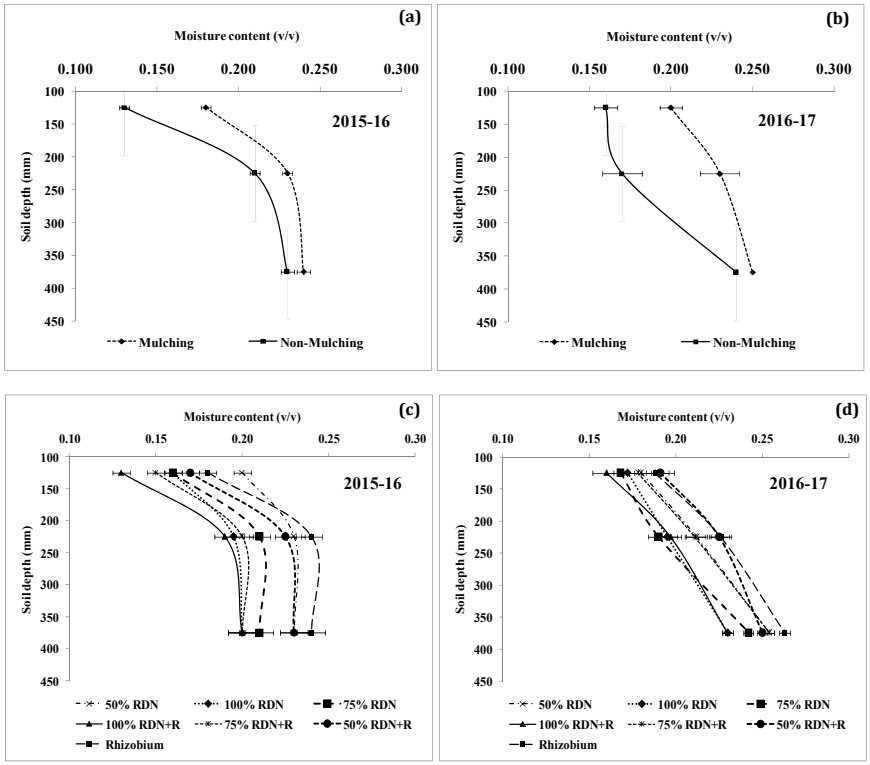


Figure 6. Effect of mulch (**a**,**b**) and nutrient dose (**c**,**d**) on soil moisture content (*v*/*v*) at pod formation of peanut (data from 2015–2016 and 2016–2017 crop seasons, respectively); error bars represent the least significant difference value.

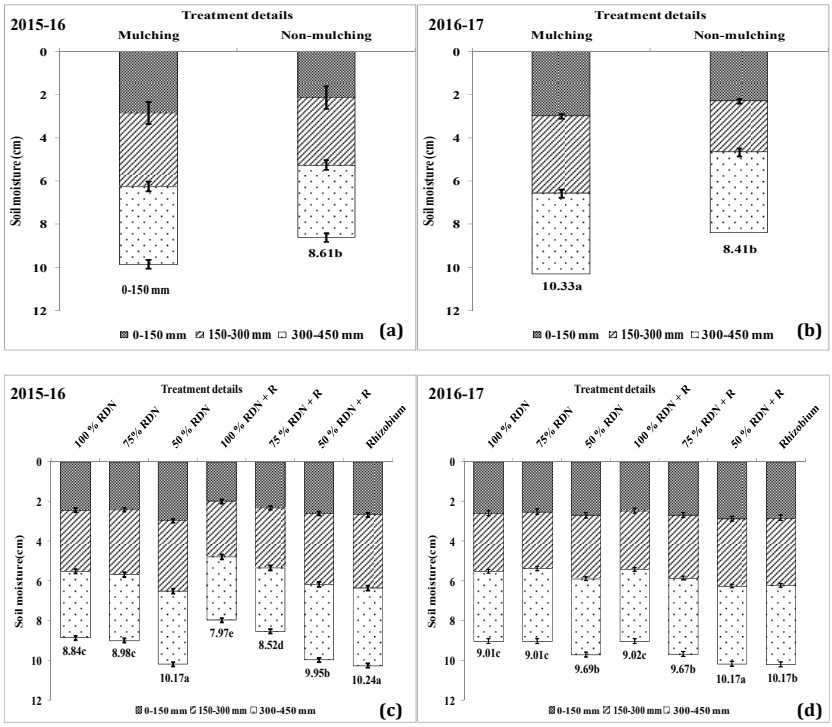


Figure 7. Effect of mulch (**a**,**b**) and nutrient dose (**c**,**d**) on root zone moisture storage (cm) at pod formation of peanut(data from 2015–2016 and 2016–2017 crop seasons, respectively); within treatments, numbers followed by different letters indicate significant differences at $p \leq 0.05$ (otherwise statistically at par); error bars represent the least significant difference value.

The winter peanut growing season is November to March, which is the dry season in India. Low rainfall and lack of soil moisture significantly inhibit crop yields [64]. Mulching retains soil moisture in the root zone by reducing the evaporative loss from the topsoil surface [65]. The formation of a dry layer in the topsoil is strongly influenced by high evaporation, greater soil bulk density, and moisture uptake by the plant. This dry upper layer reduces evaporative loss from deeper soil layers, resulting in higher soil water retention in deeper, root-accessible layers during the dry season [60].

3.5. Nutrient Dynamics are Influenced by Different Levels of Nitrogen in Association with Rh and Soil Mulch

The nutrient concentrations in the peanut kernel and haulm are shown in Figure 8. The highest N concentrations were recorded in the treatments with mulch; concentrations were not significantly different between growing seasons (Figure 8a,b). A similar trend was observed by Subrahmaniyan et al. [66]. The treatment with 100% RDN with *Rh* resulted in significantly higher N concentration (4.03%) in the peanut kernel, which was closely followed by the treatment with 100% RDN with no *Rh* (Figure 8c); this trend was observed in both seasons. In the second experimental season, the lowest N concentration (3.52%) in the peanut kernel was found in the treatment thatdid not receive any chemical fertilizer (Figure 8d). Other researchers have reported that biofertilizers, which have N-fixing abilities, contribute to higher N accumulation by plants [67]. Biofertilizers initially immobilize available soil N, enhancing its availability at later stagesof plant growth and reducing N loss; as well, they can directly improve N uptakes by the peanut plant by facilitating the conversion of ammonia to nitrate [68]. Mathenge et al. [19] demonstrated that fertilizing with mineral N combined with *Bradyrhizobium* inoculation maximized the shoot N concentration in leguminous crops. This has the potential to improve plant growth and plant root system development, which in turn would improve plant N uptake.

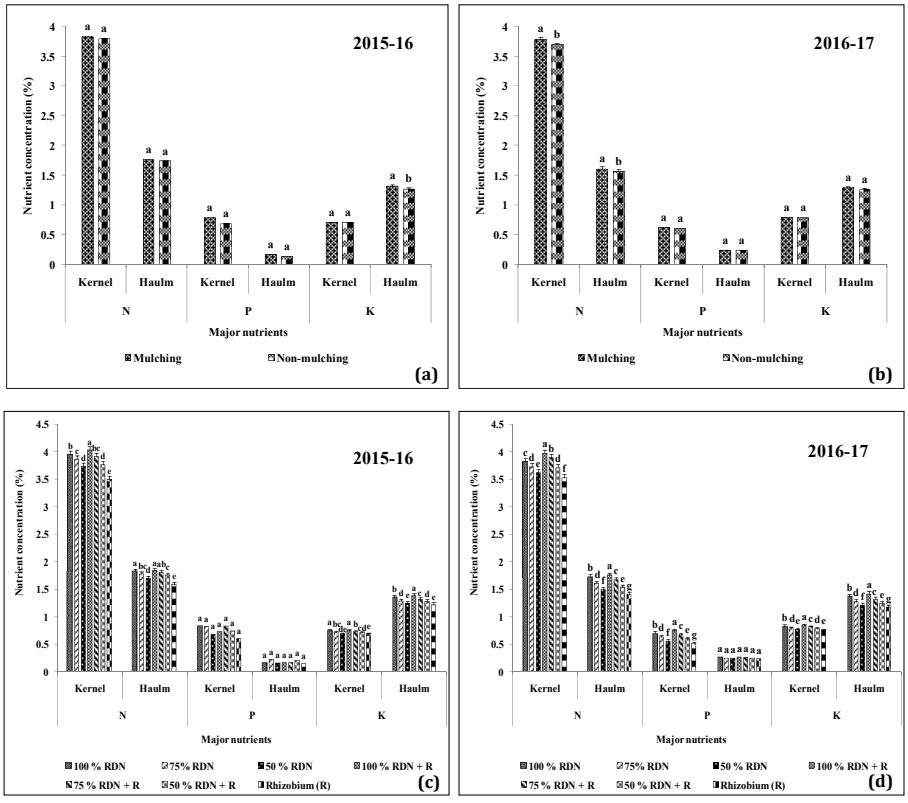


Figure 8. Effect of mulch (**a**,**b**)and nutrient dose (**c**,**d**) on nutrient concentration (%) in different plant parts at harvest of peanut (data from 2015–2016 and 2016–2017 crop seasons, respectively); within treatments, different letters indicate significant differences at $p \leq 0.05$ (otherwise statistically at par); error bars represent the least significant difference value.

No significant differences were recorded between treatments in terms of P concentration in peanut kernel and haulmin the first growing season (Figure 8a,c). However, in the second season, the P concentration was significantly affected by mulching and nutrient management: the treatment with 100% RDN with *Rh* and mulch had 0.63% higher P in the kernel, and the treatment with 100% RDN with *Rh* but no mulch had 0.73% higher P in the kernel than all other treatments (Figure 8b,d).

K concentration in the kernel did not significantly differ between mulched and non-mulched treatments; however, it differed with the amount of N fertilizer applied. The highest K concentration in the kernel (0.74% and 0.84% in the first and second seasons, respectively) was recorded in the treatment with 100% N with *Rh* (Figure 8b,d). Mulching also significantly ($p \leq 0.05$) improved K concentration in the peanut haulm. Among the N treatments, the highest K concentration (1.41% K) was observed from that with100% RDN with *Rh* (Figure 8d).

Mulch, which acted as a physical barrier to rainfall, reduced the leaching of major nutrients beyond the root zone. Additionally, lower weed competition under mulching may have increased the number of macronutrients available to the crop [69]. Treatments with higher rates of N combined with *Rh* inoculation resulted in better N, P, and K concentrations in the peanut kernel and haulm [47]. This may be a result of improved nutritional environment in the rhizosphere as well as in plant systems, enhancing the translocation of nutrients between plant parts. An increase in nutrient uptake due to *Rh* inoculation has been reported from many research studies globally: even where yield enhancement was not apparent, *Rh* inoculation still increased the soil N level and plant N uptake [70]. Rhizobia may solubilize soil P through the production of low molecular weight organic acids that act on inorganic phosphorus [71]. Schütz et al. [68] suggested that incorporating a biofertilizer *Rh* with traits such as N fixation or P solubilization could have a more synergistic effect on legume crops than on other crops. *Rh* can synthesize phytohormones such as auxin as secondary metabolites in an inoculated plant; these play a vital role in plant-growth regulation, resulting in improved root development and proliferation leading to higher nutrient uptake [72].

3.6. Nutrient Balance in Peanut is Influenced by the Different Levels of Nitrogen in Association with Rh and Soil Mulch

A nutrient balance indicates the net gain or loss of nutrients in the soil post-harvest [73]. In the first growing season, the available soil N declined in treatments with lower rates of applied N and reached a negative value in the 50% RDN treatment (Table 4). Irrespective of N applied, the non mulched treatments always had higher available N than the mulched treatments. This may be due to the lower N uptake and reduced peanut crop yield under non-mulched conditions. Compared with the initial soil status, the actual gain of N was highest (21.50 kg ha^{-1}) in the treatment with 75% RDN with *Rh* inoculation and no mulch. This N gain was 81.89% greater than the treatment with the same N and *Rh* and with mulch.

After the second growing season (Table 5), the maximum net gain of N was observed in the treatment with 100% RDN with *Rh* inoculation (9.72 kg ha^{-1}) under non-mulching conditions, which was closely followed by the treatment with 75% RDN with *Rh* (6.51 kg ha^{-1}) with no mulch. This was possibly a consequence of the better post-harvest residual soil N status (223.42 and 220.20 kg ha^{-1}, respectively). When peanut was grown under mulch but without applied N, the maximum available soil N declined (−30.77 kg ha^{-1}) from the initial to the post-harvest observation. A higher expected N balance (154.12 kg ha^{-1}) and a lower apparent balance (34.44 kg ha^{-1}) were observed in the treatment with *Rh* applied without mulch or fertilizer. We observed that available soil N was always higher post-harvest than in the initial condition in all treatments where mineral N with *Rh* was applied.

Table 4. Nutrient balance of peanut under different mulch and nutrient management practices (2015–2016).

Treatments	Initial N (kg ha^{-1}) (A)	Fertilizer N Added (kg ha^{-1}) (B)	Total N (kg ha^{-1}) (A + B)	Total N Uptake (kg ha^{-1}) (C)	Expected Balance {(A + B) − C} (D)	Post-Harvest Soil N Status (kg ha^{-1}) (E)	Apparent Balance, Gain (E − D) or Loss (D − E) (F)	Actual Gain (E − A)/Loss (A − E) (G)
Mulching								
100% RDN	195.3	25.0	220.3	180.8	39.5	201.4	161.9	6.15
75% RDN	195.3	18.7	214.0	168.3	45.79	192.4	146.7	−2.8
50% RDN	195.3	12.5	207.8	152.9	54.86	183.6	128.6	−11.8
100% RDN + *Rh*	195.3	25.00	220.3	199.8	20.50	205.6	185	10.2
75% RDN + *Rh*	195.3	18.7	214.0	182.9	31.12	207.1	176.00	11.8
50% RDN + *Rh*	195.3	12.5	207.8	169.9	37.88	196.3	158.4	1.0
Rhizobium (*Rh*)	195.3	0	195.3	74.8	120.54	176.5	56.0	−18.8
Non-mulching								
100% RDN	195.3	25.00	220.3	150.2	70.13	207.2	137.0	11.9
75% RDN	195.3	18.7	214.0	138.0	75.96	200.3	124.4	5.0
50% RDN	195.3	12.5	207.8	125.0	82.71	192.5	109.8	−2.8
100% RDN + *Rh*	195.3	25.0	220.3	157.9	62.37	212.5	150.1	17.2
75% RDN + *Rh*	195.3	18.7	214.0	146.8	67.20	216.8	149.6	21.5
50% RDN + *Rh*	195.3	12.5	207.8	131.6	76.23	205.2	129	9.9
Rhizobium (*Rh*)	195.3	0	195.3	62.5	132.79	183.24	50.4	−12.0

RDN, recommended dose of nitrogen: 100% = 25 kg ha^{-1}.

Table 5. Nutrient balance of peanut under different mulch and nutrient management practices (2016–2017).

Treatments	Initial N (kg ha^{-1}) (A)	Fertilizer N Added (kg ha^{-1}) (B)	Total N (kg ha^{-1}) (A + B)	Total N Uptake (kg ha^{-1}) (C)	Expected Balance {(A + B) − C} (D)	Post-Harvest Soil N Status (kg ha^{-1}) (E)	Apparent Balance, Gain (E − D) or Loss (D − E) (F)	Actual Gain (E − A)/Loss (A − E) (G)
Mulching								
100% RDN	213.7	25.0	238.7	192.5	46.2	207.12	160.9	−6.6
75% RDN	213.7	18.7	232.4	169.6	62.9	205.2	142.3	−8.5
50% RDN	213.7	12.5	226.2	154.8	71.4	194.5	123.0	−19.2
100% RDN + *Rh*	213.7	25.0	238.7	208.1	30.6	217.2	186.6	3.5
75% RDN + *Rh*	213.7	18.7	232.4	182.6	49.8	215.3	165.4	1.6
50% RDN + *Rh*	213.7	12.5	226.2	167.1	59.0	200.6	141.6	−13.0
Rhizobium (*Rh*)	213.7	0	213.7	71.0	142.6	182.9	40.3	−30.8
Non-mulching								
100% RDN	213.7	25.0	238.7	159.01	79.7	212.6	132.9	−1.0
75% RDN	213.7	18.7	232.4	143.7	88.8	215.2	126.7	1.5
50% RDN	213.7	12.5	226.2	128.4	97.8	200.8	103	−12.9
100% RDN + *Rh*	213.7	25.0	238.7	167.6	71.0	223.4	152.3	9.7
75% RDN + *Rh*	213.7	18.7	232.4	157.3	75.1	220.2	145.0	6.5
50% RDN + *Rh*	213.7	12.5	226.2	137.7	88.5	209.5	121	−4.2
Rhizobium (*Rh*)	213.7	0	213.7	59.6	154.1	188.6	34.4	−25.1

RDN, recommended dose of nitrogen: 100% = 25 kg ha^{-1}.

4. Conclusions

This research has quantified peanut productivity and yield-attributing traits and evaluated the kernel quality, plant nutrient uptake, moisture distribution at different soil depths, and rhizospheric microbial activity under mulched and non-mulched treatments combined with precision N management practices with and without *Rh* inoculation. Our results indicate that the maximum increases in yield attributes, pod yield, kernel yield, and biological yield were obtained from the treatment with highest N application (100% RDN) combined with *Rh* inoculation and under mulch. There was little difference between pod yield between this treatment with 100% RDN and the comparable treatment with 75% RDN; however, kernel yield and attributes of quality (i.e., oil and protein yield) were significantly improved in the 100% RDN treatment with *Rh* and mulch. Treatments with a high N dose were not adversely affected in terms of root nodulation or soil microbial count. Higher soil moisture distribution and root zone moisture storage were recorded under mulched treatments. Crop N uptake was highly

correlated with pod yield. After two experimental growing seasons, the greatest increases in soil available nitrogen were observed in the treatments with 100% RDN combined with *Rh*, irrespective of mulching practice. Our findings suggest that incorporating polythene mulch with *Rh* seed inoculation in peanut cultivation will greatly increase crop productivity and soil health when the crop is fertilized with the full recommended dose of N (i.e., 25 kg ha^{-1}) for peanuts grown in the new alluvial zone of India and in comparable agro-ecological zones.

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

Funding: This research was funded by ICAR-AICRP on Groundnut, Kalyani Centre, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, West Bengal, India and the APC was funded by the projects: VEGA 1/0589/19 and VEGA 1/0683/20.

Acknowledgments: The authors sincerely acknowledge the contributions of the Department of Agronomy of Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, West Bengal, India for providing necessary laboratory facility during the investigation. The authors are highly grateful to field staffs of District Seed Farm, BCKV, Kalynai for necessary technical helps during the field experiment period.

Conflicts of Interest: There is no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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