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Research Article

The effects of nitrogen and phosphorus fertilizer levels and various biofertilizer sources on baby corn yield, yield attributes, quality, soil nutrients, and economic viability: A sustainable and cost-effective approach

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ABSTRACT

This study explores the cultivation of baby corn and its evolving role in product diversification and value addition within agricultural systems. Baby corn, a versatile vegetable harvested just before silk emergence, has a nutritional content comparable to that of non-legume vegetables. The research examines the effects of nitrogen and phosphorus fertilizers, along with various biofertilizer sources, on baby corn yield, yield attributes, quality, soil status, and economic factors. Twelve distinct treatment combinations were applied, featuring three levels of nitrogen (60, 80, and 100 kg ha^{-1}) and two levels of phosphorus (50 and 75 kg ha^{-1}), combined with *Azotobacter* and *Azospirillum* biofertilizers. Evaluation criteria included crop yield, plant height, ear length, cob diameter, and financial returns. Results highlight the significant impact of *Azospirillum* on baby corn production and its associated attributes. The most effective treatment, N3P 2AS (100 kg N and 75 kg P_2O_5 *via Azospirillum*), yielded superior green fodder and baby corn. This treatment achieved an exceptional Benefit-Cost Ratio (BCR) of 2.94, with the highest net return of Rs. 2348.3 USD ha^{-1}. Following closely, the application of 60 kg N and 50 kg P *via Azotobacter* resulted in a net return of Rs. 962.6 USD ha^{-1} and a BCR of 1.28. Notably, combining 100 kg N and 75 kg P with *Azotobacter* produced higher levels of carbohydrates (8.73%), protein (4.66%), total sugars (17.86%), starch (74.10%), ascorbic acid (8.27%), and NPK contents (0.69, 0.16, and 0.92), with the exception of moisture content. Post-harvest soil analysis revealed improved conditions with 100 kg N and 75 kg P, showing higher levels of macro (NPK) and micro (zinc, copper, iron, manganese, and sulfur) nutrients compared to alternative treatments. This underscores the beneficial impact of combined nitrogen-phosphorus and biofertilizer applications on both soil nutrients and baby corn quality. The study emphasizes the importance of employing integrated nutrient management strategies to maximize the profitability and productivity of baby corn. It offers practical insights for farmers seeking to enhance yields and economic returns while advocating for bio-organic fertilization as a sustainable alternative to chemical inputs, positively impacting both baby corn quality and soil nutrient enrichment.

Keywords: Baby corn, N and P fertilization, Biofertilizer, Yield attributes, Soil properties nutrient status, Quality economic viability

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Abbreviations: N: Level of nitrogen; P: Level of phosphorus; AB: *Azotobacter*; AS: *Azospirillum*; K: Potassium

INTRODUCTION

Corn is a cornerstone of India's agricultural landscape, ranking among the country's vital crops alongside rice and wheat. In recent years, baby corn has surged in popularity, particularly in countries such as the United States, Japan, Singapore, Australia, Canada, New Zealand, and across the Arab world. This growing interest can be attributed to baby corn's remarkable nutritional content, adaptability, and short shelf life. Even within rural Indian communities, there has been a noticeable increase in its consumption. Baby corn is harvested just two to three days after silking, but before fertilization, representing an immature ear of corn that has undergone dehusking. Baby corn (*Zea mays* L.) is cultivated for its young, fresh, finger-like green ears, which are harvested at the time of silk emergence. It can be eaten raw and is processed in various ways, including in soups, salads, pasta, dry vegetable dishes, curries, pickles, snacks, candy, jams, intercontinental dishes, and canning (Belay et al., 2023).

The nutrient balance of soil is crucial for maintaining productivity and achieving optimal yields and quality in baby corn. Notably, the total quantity of nutrients extracted annually by crops and cropping systems often exceeds the amount provided through fertilizers. For instance, studies by Patil et al. and Kumar et al., found that baby corn crops performed better and yielded higher when supplied with a balanced array of nutrients. Research conducted by Dawson et al. highlighted that a productive strain of *Azospirillum* can significantly enhance crop yield and nitrogen fixation in soils with low nitrogen levels. High-yielding crop varieties frequently require chemical fertilizers to meet their concentrated nitrogen demands. These fertilizers typically contain nitrogen in the forms of amide (NH_2-), NH_4^+, NO_3^-, or a combination of these. Ammonium sulfate, which contains 20.6% nitrogen, is one such fertilizer. It promotes root growth and maturation, similar to phosphorus, which is known to stimulate healthy root development and fruit ripening. According to Bhaladhare et al., this nutrient fulfills only about 0.2% of the overall dietary requirement. However, despite its small contribution, it is irreplaceable and essential for plant growth and development.

The preference for baby corn encompasses a wide range of culinary uses, from the popular Manchurian dish to desserts like halwa and kheer, as well as condiments such as chutney and pickles. According to Das et al., (2009) this petite corn variant boasts impressive nutritional credentials, containing 89.1% moisture, 0.2 g of fat, 1.9 g of protein, 8.2 g of carbohydrates, 0.06 g of ash, 28.0 mg of calcium, 86.0 mg of phosphorus, and 11.0 mg of ascorbic acid per 100 g. Moreover, baby corn's nutritional benefits are enhanced by its pesticide-free nature, which is attributed to its rapid development timeline that minimizes exposure to diseases and pests.

The global market for baby corn is driven by its appealing taste, nutritional richness, freshness, absence of pesticides, and culinary versatility, positioning it as a contender for a "green meal". As an agricultural commodity, baby corn has significant potential for generating foreign exchange through international trade. However, maintaining its quality—requiring high nutrient levels—is crucial for meeting international standards. In this context, the methodologies employed to fulfill these nutritional requirements play a vital role in ensuring the quality of baby corn while also preserving soil health.

Recent studies, including those by Joshi and Chilwal, highlight the effectiveness of inoculating maize seeds with *Azospirillum* and *Azotobacter* in enhancing the content of carbohydrates, proteins, starch, total sugars, and minerals in maize. This not only improves the nutritional profile of baby corn but also underscores the importance of sustainable agricultural practices. Amid the challenges posed by the increasing difficulty and cost of obtaining agrochemical supplies—particularly biofertilizers that are essential for modern agriculture—there is a growing demand for alternative technologies.

Recognizing the environmental impact of conventional agrochemicals, the adoption of non-toxic and environmentally friendly biofertilizers has emerged as a viable solution. While biofertilizers cannot entirely replace chemical inputs, their integration with inorganic nutrient sources can significantly contribute to preserving soil health, reducing dependence on fossil fuels, and maintaining product quality. This dual approach not only aligns with environmental sustainability but also offers a cost-effective alternative to conventional fertilization methods. Integrated nutrient management involves using biofertilizers either alone or in conjunction with chemical fertilizers. To maximize baby corn yields in the Tarai region of Allahabad, Uttar Pradesh, India, it is crucial to enhance the integration of chemical fertilizers and biofertilizers. With this in mind, the current study aims to determine whether integrated nutrient management can improve baby corn yields and identify the specific attributes that contribute to yield and economic viability.

MATERIALS AND METHODS

Experimental site

The experimental site for this study was the Crop Research Farm, Block E, of the SHUATS Model Organic Farm (SMOF), which is affiliated with the Department of Agronomy at the Allahabad School of Agriculture, Sam

Higginbottom University of Agriculture, Technology, and Sciences. This farm is located in Prayagraj, Uttar Pradesh, India. The experiment took place during the summer season of 2019, at coordinates 25°24'42" N latitude and 81°50'56" E longitude, with an altitude of 98 meters above sea level. Situated on the right side of the Yamuna River, the farm is along Allahabad Rewa Road, approximately five kilometers from Allahabad city (Figure 1).

The specific location details, including latitude, longitude, and altitude, provide a comprehensive understanding of the experimental site's geographic positioning. These details are crucial for understanding the environmental context in which the experiment was conducted and contribute to the replicability and accuracy of the study.

The climatic and weather conditions during the experimental period were meticulously monitored by collecting weekly meteorological data. This data included information on maximum and minimum temperatures, relative humidity, daily sunshine hours, and rainfall. It was gathered from the Meteorological Observatory at the School of Forestry and Environment, Sam Higginbottom University of Agriculture, Technology, and Sciences, located in Prayagraj, Uttar Pradesh. The Meteorological Observatory at SHUATS provided a reliable source for obtaining accurate and timely meteorological information. This data was instrumental in assessing the prevailing climatic conditions, which are critical factors influencing agricultural experiments. The recorded values for these meteorological parameters throughout the experimental period are summarized in Figure 2, offering a comprehensive overview of the climate during the study period.

Figure 1. Map of the study area, Prayagraj, Uttar Pradesh, India.

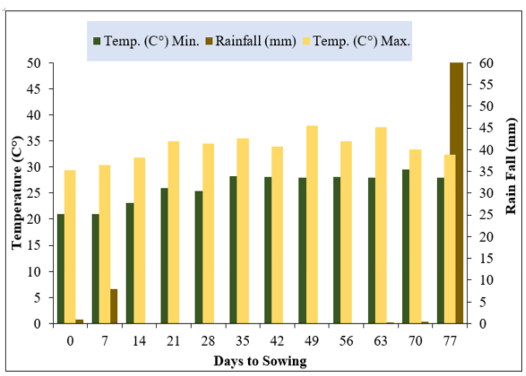

Figure 2. Rainfall (mm) and average minimum (°C) and maximum (°C) air temperatures recorded during the summer growing season of the agricultural year 2019 in Rewa, Prayagraj, Northern India.

The soil classification of the experimental area was determined using the Bouyoucos hydrometer method, which categorized it as medium-textured sandy loam. This classification revealed a soil composition of 59.31% sand, 26.38% silt, and 11.31% clay. Prior to the experiment, comprehensive chemical and physical analyses were conducted on the soil at a depth of 15 cm. The average values obtained from these analyses are as follows: pH: 7.40, determined using the glass electrode pH meter method; electrical conductivity (EC): 1.31 dS/m, measured according to Method No. 4 from USDA Handbook No. 16; Organic Carbon (OC): 0.39%, analyzed using the Walkley and Black method; available nitrogen: 170.35 kg ha^{-1}, assessed through the Walkley and Black method; available phosphorus: 15.50 kg ha^{-1}, determined by Olsen's colorimetric method; available potassium: 261.00 kg ha^{-1}, measured using the flame photometer method; available zinc: 0.85 ppm, assessed using the DTPA extractable method; available copper: 11.39 ppm, determined through the DTPA extractable method; available iron: 11.17 ppm, analyzed using the DTPA extractable method; available manganese: 1.00 ppm, assessed *via* the DTPA extractable method; and available sulfur: 11.27

ppm, measured using the turbidimetric method. Similarly, at the end of the experiment during the growing season, physicochemical analyses of the soil were conducted for each treatment after the harvest of baby corn.

Experimental design and treatments

The experimental design employed a complete block design with twelve randomized treatment combinations and three replications. The random allocation of treatments within each replication resulted in the formation of 36 plots, providing a robust and statistically sound framework for the experiment. The treatments consisted of a combination of two seed inoculations—based on *Azospirillum* (AS) strain and *Azotobacter* (AB)—four levels of nitrogen fertilization (N1: 60 kg ha^{-1}, N2: 80 kg ha^{-1}, N3: 100 kg ha^{-1}), and two levels of phosphorus (P1: 50 kg ha^{-1} and P2: 75 kg ha^{-1}). The field experiments were conducted during the summer growing season of 2019.

Field management

Test crop and cultivar: The certified baby corn hybrid G-5414 seeds were provided by Syngenta Pvt. Ltd. in Maharashtra, India, on behalf of Amar Paradigm, a private seed company. These plants grow rapidly, reaching heights of 1.80 to 2.00 meters. Each plant produces two to three ears of corn that are similarly sized, measuring 8 to 10 cm in length. After sowing, the tender ears can be harvested 55 to 65 days later, with the harvesting period lasting from 8 to 10 days (Franche et al., 2008).

Pre-sowing operations: To simplify the sowing process, the experimental field was first prepared using a tractor-drawn plow. It was then cultivated with two cultivators and harrows, followed by planking. Individual plots were established within the experimental field, and each plot was manually leveled. The G-5414 variety of baby corn was used as the test crop in this study. Before sowing, one hundred seeds of this variety were collected. In the laboratory, a germination test was conducted using filter paper and a Petri dish. The baby corn seeds had an overall germination percentage of 95%, and the quantity of seeds was adjusted accordingly. The experimental procedure involved utilizing a commercial liquid inoculant containing strains of *Azospirillum* and *Azotobacter* to inoculate the popcorn seeds (IAC125) intended for producing baby corn. The manufacturer's specifications guaranteed a minimum concentration of 2×10^8 viable cells per milliliter in the inoculant. The inoculation process was carried out meticulously, using plastic bags designated for each treatment in a dry and shaded environment, immediately prior to the seeding phase. To ensure a uniform coating of the seeds with the inoculant, the bags were vigorously shaken. Subsequently, the treated seeds were carefully transported to the field in Styrofoam boxes, with precautions taken to shield them from direct sunlight until planting. This methodological approach underscores attention to detail and adherence to best practices in applying the liquid inoculant, emphasizing the maintenance of optimal conditions for the viability and efficacy of the microbial strains. The use of designated bags for each treatment minimizes the risk of cross-contamination, while the transportation and storage protocols further safeguard the integrity of the inoculated seeds. This contributes to the reliability and reproducibility of the experimental outcomes. The remaining Nitrogen (N) was top-dressed when the baby corn reached knee height, and chemical fertilizers were applied at sowing at a baseline dose of 120:60:40 kg ha^{-1} (N: P_2O_5: K_2O). Robust and healthy seeds were chosen for sowing. In April 2019, baby corn was manually seeded with two seeds per hill at a 20 cm intra-row spacing on one side of a ridge. The seeds were basal-treated and sown at the recommended depth of 5 cm in the open furrow, then covered with topsoil and gently pressed.

Post-sowing cultural operations: To maintain a consistent plant population throughout the experimental season, gap filling was conducted 14 Days After Sowing (DAS) in certain plots where emergence was insufficient. During the growing season, surplus plants were removed from component crops at 15 DAS to ensure a plant-to-plant spacing of five centimeters, thereby minimizing competition. Hand weeding was performed at regular intervals to control existing weeds, with the first weeding occurring at 22 DAS and the second at 42 DAS. An effective and natural method for termite removal involved using a combination of wood vinegar and neem oil. This mixture helps control insect growth and prevents molting, ultimately leading to their extinction. For application, 100 milliliters each of wood vinegar and neem oil were mixed with ten liters of water and applied *via* foliar spraying. Irrigation was provided based on weather conditions and crop requirements. Detasseling is a crucial step in baby corn cultivation. During the experimental season, detasseling was performed twice, at 53 and 56 DAS, by removing the tassels as soon as they emerged from the flag leaf but before they began to discharge pollen. The tassels were removed by jerking them upward while holding them firmly with one hand. Detasseling continued on a smaller scale until 63 DAS to accommodate sporadic tassel emergence. Throughout the experimental season, five pickings of fresh baby corn were conducted on days 59, 61, 64, 66, and 69 DAS. Baby corn was picked when the silk separated from the top of the ears by three to four centimeters. Harvesting took place in the morning when the baby corn had the highest moisture content and the outside temperature was at its lowest. After harvesting, the yield from 1.35 m^2 was recorded, converted to tons per hectare, and weighed. Following the harvest, the plants were cut using a sickle, and necessary by-product data was recorded. The remaining plant material was fed to cattle as green fodder. After the picking process, the girth, length, and weight of the cobs (including husk) were measured. The cobs were then manually dehusked, and the husk was carefully removed to collect data on the girth, weight, and length without the husk. Finally, grading and packing were carried out for local sales.

Measurements and calculations

Yield and yield attributes: The appropriate sampling techniques were employed to collect data and conduct subsequent analyses. A zigzag pattern was used to randomly select five plant samples from each plot, ensuring that the harvest zone and border rows or plants were avoided. Five plants were obtained through destructive sampling to gather the required data, and these tagged samples were used to record yield measurements at maturity. The average number of cobs per plant was calculated using the five randomly selected plants. The length of each cob was measured both with and without its husk using a scale. The diameter of each cob was measured with vernier calipers, and the cob girth was calculated by multiplying the diameter by π (3.14), with the result expressed in centimeters. The weight of each cob was measured with and without its husk using a weighing balance. Each plot had an area of 1.35 m^2 harvested, while the plants in the border row and sampling zone remained untouched. A yield analysis was conducted based on hectares, with the cobs from each plot's 1.35 m^2 area dehusked and weighed separately. Following the harvest of the baby corn cobs, green fodder was collected from each plot's 1.35 m^2 area, and the yield was calculated in tons per hectare (t ha^{-1}). The harvest index was calculated by dividing the economic yield (green cobs) by the biological yield (green cobs plus green fodder). This calculation was performed for each plot using a standardized formula, and the result was expressed as a percentage.

$$\text{Harvest Index (\%)} = \frac{\text{Economic Yield}\left(\frac{\text{t}}{\text{ha}}\right)}{\text{Biological Yield}\left(\frac{\text{t}}{\text{ha}}\right)} \times 100$$

Economic analysis: For each treatment combination, the economics of crop production and cultivation were calculated separately on a per-hectare basis. Notably, the cost of cultivation (USD $/ha) for each treatment was calculated, encompassing all cultural methods employed throughout the cultivation process. Both product yield and market price were considered when calculating the gross return (USD $/ha) for each treatment combination. Additionally, the net return (USD $/ha) for each treatment was calculated using the following formula:

$$\text{Net return (USD \$ ha}^{-1}) = \text{Gross return (USD \$ ha}^{-1}) - \text{Cost of cultivation(USD \$ ha}^{-1}) \quad (2)$$

By subtracting the cultivation costs from the gross returns, we determined the net return for each treatment combination, providing a clearer picture of the profitability of each method. Additionally, the benefit-cost ratio was calculated separately for each treatment combination using the formula below:

$$\text{B: C ratio} = \frac{\text{Net return (USD \$ ha}^{-1})}{\text{Cost of cultivation(USD \$ ha}^{-1})} \quad (3)$$

By dividing the net return by the cost of cultivation, we calculated the benefit-cost ratio for each treatment combination. This ratio provides valuable insights into the potential profitability of each method by comparing the net return with the cost of cultivation.

Note: As of July 1, 2019, $1 (US dollar) is equivalent to ₹68.09 in Indian Rupees. This conversion rate can be useful for analyzing the economics of crop production and cultivation in India or for comparing costs and returns across different countries.

Quality analysis: The quality analysis of baby corn cobs involved determining nitrogen content using the modified Kjeldahl method. The nitrogen content obtained from both the cobs and seeds was multiplied by a factor of 6.25 to convert it into protein, expressed as a percentage. To estimate the carbohydrate content of the baby corn cobs, the Anthrone method, as suggested by Hedge and Hofreiter, was employed. In this method, 100 mg of the sample was placed in a boiling tube and hydrolyzed in a boiling water bath for three hours with 5 ml of 2.5 N HCl. After cooling to room temperature, the sample was neutralized with solid sodium carbonate until effervescence ceased. The volume was then adjusted, and the mixture was centrifuged, with the supernatant collected. Aliquots of 0.5 and 1.0 ml were taken for analysis. For the preparation of standards, 0, 0.2, 0.4, 0.6, 0.8, and 1.0 ml of the working standard were used, with the zero-standard serving as the blank. The volume in all tubes, including the sample tubes, was adjusted to 1 ml by adding distilled water. Subsequently, 4 ml of Anthrone reagent was added, and the mixture was heated for 8 minutes in a boiling water bath. The absorbance of the resulting green to dark green color was measured at 630 nm. This analytical approach enabled the accurate determination of nitrogen and carbohydrate content in the baby corn cobs, providing valuable insights into their nutritional composition.

Chemical analysis of soil: The chemical analysis of the soil involved collecting samples from each treatment after harvesting the crops during the experimental season. The analysis included various parameters, such as organic carbon, available nitrogen, available phosphorus, available potassium, available zinc, available copper, available sulfur, available manganese, available iron, and pH. The pH of the soil was determined electrometrically. Ten grams of air-dried soil were placed in a 100 ml beaker, and 25 ml of distilled water was added. The mixture was vigorously stirred for 20 minutes, and after allowing the suspended clay to settle, the pH meter was calibrated at pH 4 and 7. The electrode of the pH meter was then inserted into the suspension, and the reading was recorded. To determine the organic carbon percentage, the Walkley and Black method was utilized. Two grams of soil were weighed into a 500 ml flask, to which 10 ml of 1.0 N potassium dichromate and 20 ml of sulfuric acid (H_2SO_4) were added. The mixture was swirled and allowed to cool for 30 minutes. Subsequently, 200 ml of distilled water and 10 ml of orthophosphoric acid were added, and titration with 1.0 N ferrous sulfate solution was performed, with the reading noted. Total nitrogen content was determined using the modified Kjeldahl method. 10 ml of distilled water was added to 10 grams of air-dried soil in a 500 ml Kjeldahl flask, followed by the addition of a Kjeldahl catalyst and concentrated H_2SO_4. After digestion, distillation and titration with 0.1 N HCl were carried out to determine the percentage of nitrogen. For the estimation of available phosphorus, 5 grams of soil were placed into a 250 ml Erlenmeyer flask containing 100 ml of 0.5 N $NaHCO_3$ solution. The filtrates were collected and analyzed using a colorimetric method with a spectrophotometer. The potassium concentration was determined by shaking 5 grams of soil with 20 ml of Diethylene Triamine Pentaacetic Acid (DTPA) extracting solution, followed by flame photometry. To estimate available zinc, iron, copper, and manganese, 10 grams of air-dried soil were shaken with 20 ml of DTPA extracting solution, and the content was analyzed using an Atomic Absorption Spectrophotometer (AAS).

Chemical analysis of plant samples for determination of nutrient uptake: The chemical analysis of plant samples for nutrient uptake involved preparing various plant parts, including cobs, tassels, young husks, silks, green stalks, and roots of baby corn from individual treatments. Each plant part was dried separately, and the dried samples were then ground into a powder using a Willey mill with stainless steel blades. The resulting powdered plant samples were used for nutrient analysis. To determine the nitrogen content in the plant samples, the powdered material underwent digestion. This process involved treating the plant samples with concentrated sulfuric acid and a digestion mixture composed of Potassium Sulfate (K_2SO_4), Copper Sulfate ($CuSO_4$), and selenium powder in a ratio of 100:20:1. After complete digestion, the contents were transferred to a distillation unit (Micro Kjeldahl), where the liberated ammonia was trapped in boric acid. The trapped ammonia was then back-titrated with standard acid (HCl) to estimate the nitrogen content in the plant samples. The percentage of Nitrogen (N%) in the plant samples was calculated using the following formula:

$$\text{N}(\%) = \frac{\text{Titrated value} \times \text{N of acid} \times 0\cdot014 \times \text{Valume of digested sample}}{\text{Weight of sample} \times \text{Aliquot taken}} \times 100 \qquad (4)$$

This formula enables the accurate calculation of the nitrogen content in plant samples based on the volume and normality of the standard acid used in back titration, the atomic weight of nitrogen (14.01 g mol^{-1}), and the weight of the sample.

For the determination of Phosphorus (P) and Potassium (K) content in the plant samples, a standardized procedure was followed. Initially, a known quantity of the powdered plant sample was pre-digested with concentrated nitric acid overnight. Subsequently, digestion was carried out using a 5 ml diacid mixture (HNO_3+$HClO_4$) until a clear solution was obtained. The resulting residue was dissolved in 6 N HCl, and the volume was adjusted to 50 ml. A parallel blank was prepared using the same procedure but without the plant material. The quantification of P and K content was accomplished through the Vedo molybdate yellow color method (Erenstein et al., 2022) for phosphorus and flame photometry for potassium. For accurate measurements, spectrophotometry and a flame photometer were employed.

The percentage of phosphorus and potassium in the plant samples was calculated using the following formula (Drescher et al., 2021):

$$\text{P}(\%) = \frac{\text{Graph ppm}}{10^6} \times \frac{\text{Valume made up}}{\text{weight of the sample}} \times \text{dilution factor} \times 100 \qquad (5)$$

$$\text{K}(\%) = \frac{\text{Grapgh ppm} \times \text{Valume made up} \times \text{dilution factor}}{\text{weight of the sample taken}} \times 10 \qquad (6)$$

This formula allows for the precise calculation of phosphorus and potassium content in plant samples based on the absorbance or concentration of the sample compared to a standard. The standardized methods and analytical tools used in this process enhance the accuracy and reliability of nutrient content determination in the plant material.

To calculate nitrogen uptake by baby corn and component crops, the following formula was utilized, with results expressed in kilograms per hectare:

$$\text{N uptake (Kg ha}^{-1}\text{) by baby corn} = [\text{N content (\%) in fodder} \times \text{fodder yield Kg ha}^{-1}] + \text{N content (\%) in cob} \times \text{cob yield Kg ha}^{-1}] \qquad (7)$$

This formula takes into account the nitrogen content in the plant fodder, the corresponding dry weight of the fodder, and the total area of land under cultivation. Multiplying by 10,000 is necessary to convert the result to kilograms per hectare, providing a standardized unit for expressing nitrogen uptake by baby corn and component crops.

The calculation for phosphorus uptake was determined by multiplying the phosphorus content (expressed as a percentage) by the dry matter production (measured in kilograms per hectare). The result was then expressed in kilograms per hectare (kg ha^{-1}). The formula used for this calculation is as follows:

$$\text{Uptake (Kg ha}^{-1}\text{) by baby corn} = [\text{P content (\%) in fodder} \times \text{fodder yield Kg ha}^{-1}] + \text{P content (\%) in cob} \times \text{cob yield Kg ha}^{-1}] \qquad (8)$$

This formula takes into account the phosphorus content in the plant tissue and the dry matter production, considering the percentage of phosphorus in the plant. The result of this calculation provides the phosphorus uptake per hectare, offering a standardized unit for expressing nutrient uptake by baby corn.

The calculation for potassium uptake is determined by multiplying the potassium content (expressed as a percentage) by the dry matter production (measured in kilograms per hectare). The result is then expressed in kilograms per hectare (kg ha^{-1}). The formula used for this calculation is as follows (Bhandal et al., 1988):

$$\text{K uptake (Kg ha}^{-1}\text{) by baby corn} = [\text{K content (\%) in fodder} \times \text{fodder yield Kg ha}^{-1}] + \text{K content (\%) in cob} \times \text{cob yield Kg ha}^{-1}] \qquad (9)$$

This formula takes into account the potassium content in the plant, the dry matter production, and the percentage of potassium in the plant. The result of this calculation provides the potassium uptake per hectare, offering a standardized unit for expressing nutrient uptake in baby corn.

Statistical data analysis

In this study, we used Analysis of Variance (ANOVA) to evaluate treatment differences. We employed the SAS General Linear Model approach in IBM SPSS Statistics 27, which is particularly effective for a Randomized Complete Block Design. The methodology outlined by Gomez and Gomez (1985) helped us understand the concept of the "General" Linear Model (GLM) and its implications, thereby enhancing our comprehension of the relationship between treatments and the response variable. To compare treatment averages, we utilized Least Significant Differences (LSD) at a 5% significance level. This method allowed us to determine, with 95% confidence, which treatment combinations showed statistically significant differences in their effects on the response variable.

RESULTS

Yield and yield attributes

The data presented in Figure 3 indicate that the yield and yield attributes of baby corn—such as cob girth, cob length, cob weight, number of cobs, cob yield, and green fodder yield were significantly higher when applying a high level of nitrogen (100 kg ha^{-1}) and phosphorus (75 kg ha^{-1}) through chemical fertilizers combined with *Azospirillum* (N3P2AS). Following this, the application of nitrogen (80 kg ha^{-1}) and phosphorus (50 kg ha^{-1}) from chemical fertilizers with *Azotobacter* biofertilizer (N1P1AB) also showed substantial results.

Cob girth with and without husk (cm): Observations related to cob girth are presented in Figure 3. The treatment N3P2AS had a significant effect on cob girth. Among the various levels of nitrogen and phosphorus, along with different sources of biofertilizer under investigation, the data clearly indicate that the application of 100 kg ha^{-1} nitrogen and 75 kg ha^{-1} phosphorus with *Azospirillum* yields the best results. The girth of the cob, both with and without husk, is highest for N3P2AS (8.85 cm and 3.88 cm, respectively) and lowest for N1P1AB (5.12 cm and 2.9 cm, respectively).

Cob length with and without husk (cm): The data pertaining to cob length, both with and without husk, are presented in Figure 3. The results show that different levels of chemical fertilizer combined with various sources of biofertilizer had a significant impact on cob length. The maximum lengths of the cobs, both with and without husk, were observed in the N3P2AS treatment, measuring 24.56 cm and 15.67 cm, respectively. In contrast, the minimum lengths were recorded for the N1P1AB treatment, at 20.94 cm and 10.83 cm, respectively.

Cob weight with and husk (g cob^{-1}): The data on the effects of different application doses of nitrogen and phosphorus chemical fertilizers, combined with various sources of biofertilizers, on cob weight—both with and without husk—were found to be significant. The N3P2AS treatment (100 kg ha^{-1} nitrogen and 75 kg ha^{-1} phosphorus with *Azospirillum*) exhibited significantly higher cob weights, measuring 54.34 g with husk and 8.44 g without husk. In contrast, the lowest cob weights were recorded in the N1P1AB treatment (60 kg ha^{-1} nitrogen and 50 kg ha^{-1} phosphorus with *Azotobacter*), which were 28.15 g with husk and 5.89 g without husk.

Number of cobs per plant: The data concerning the number of cobs per plant are presented in Figure 3. The application of different levels of nitrogen and phosphorus fertilizers, along with various sources of biofertilizers, had a significant effect on the number of cobs per plant. The maximum number of cobs per plant was observed in the N3P2AS treatment, which yielded an average of 3.13 cobs per plant.

C**ob yield with and without husk (t/ha):** Data related to cob yield, both with and without husk, are presented in Figure 3. The cob yield showed significant improvement when high levels of nitrogen (100 kg ha^{-1}) and phosphorus (75 kg ha^{-1}) from chemical fertilizer were applied in combination with *Azospirillum* biofertilizer (N3P2AS), outperforming the N3P2AB treatment. The maximum cob yield was observed in the N3P2AS treatment, with yields of 8.85 kg with husk and 3.88 kg without husk. In contrast, the N3P2AB treatment recorded yields of 8.82 kg with husk and 3.81 kg without husk. The minimum cob yield was recorded in the N1P1AB treatment, with yields of 5.12 kg with husk and 2.91 kg without husk, respectively.

Green fodder yield (t/ha): Figure 3 shows that the application of different levels of nitrogen and phosphorus from chemical fertilizers, along with various sources of biofertilizers, significantly affected green fodder yield. The green fodder yield of baby corn notably increased with the application of 100 kg N ha^{-1} and 75 kg P ha^{-1} from chemical fertilizers combined with *Azospirillum* biofertilizer (N3P2AS). This treatment achieved the highest green fodder yield of 37.35 kg. In contrast, the minimum green fodder yield was observed in the N1P1AB treatment, which was 21.63 kg.

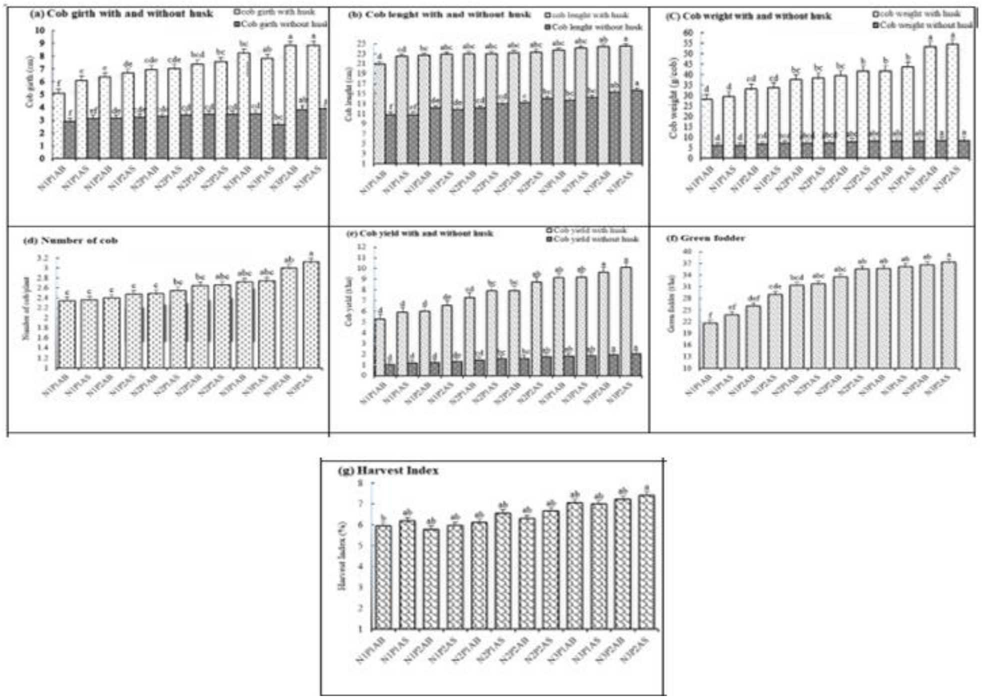

Figure 3. Impact of nitrogen, phosphorous, and bio-fertilizers on the yield and yield attributes of baby corn: (a) Cob girth with and without husk, (b) Cob length with and without husk, (c) Cob weight with without husk, (d) Number of cobs per plant, (e) Cob yield with and without husk, (f) Green fodder yield, and harvest index at harvest.

Harvest index (%): A review of Figure 3 indicates that there was no significant difference among the treatments involving different levels of nitrogen and phosphorus from chemical fertilizers combined with various sources of biofertilizers in the experiment. The maximum harvest index of 7.43% was achieved with the application of 100 kg ha^{-1} of nitrogen and 75 kg ha^{-1} of phosphorus from chemical fertilizers, along with *Azospirillum* biofertilizer (N3P2AS).

Quality

In this study, the quality of baby corn cobs was evaluated based on various parameters, including nitrogen (N), Phosphorus (P), Potassium (K), moisture, carbohydrates, protein, total sugar, starch, and ascorbic acid content. The findings, illustrated in Figure 4, revealed significant differences among the various fertilizer treatments. Specifically, the application of 100 kg ha^{-1} of nitrogen and 75 kg ha-1 of phosphorus from chemical fertilizers, combined with *Azospirillum* biofertilizer (N3P2AS), demonstrated notable outcomes compared to the treatment involving 60 kg ha^{-1} of nitrogen and 50 kg ha^{-1} of phosphorus from chemical fertilizers with *Azotobacter* biofertilizer (N1P1AB). The baby corn cobs treated with N3P2AS exhibited superior attributes, including higher levels of carbohydrates (8.73%), protein (4.66%), total sugar (17.86%), starch (74.10%), ascorbic acid (8.27%), nitrogen (0.69%), phosphorus (0.16%), and potassium (0.92%). In contrast, the N1P1AB treatment resulted in inferior quality characteristics, with lower contents of carbohydrates (8.03%), protein (3.27%), total sugar (14.46%), starch (63.74%), ascorbic acid (8.03%), nitrogen (0.59%), phosphorus (0.12%), and potassium (0.83%) (Figure 5). The only exception was the moisture content, which was significantly higher (92.86%), as depicted in Figure 3.

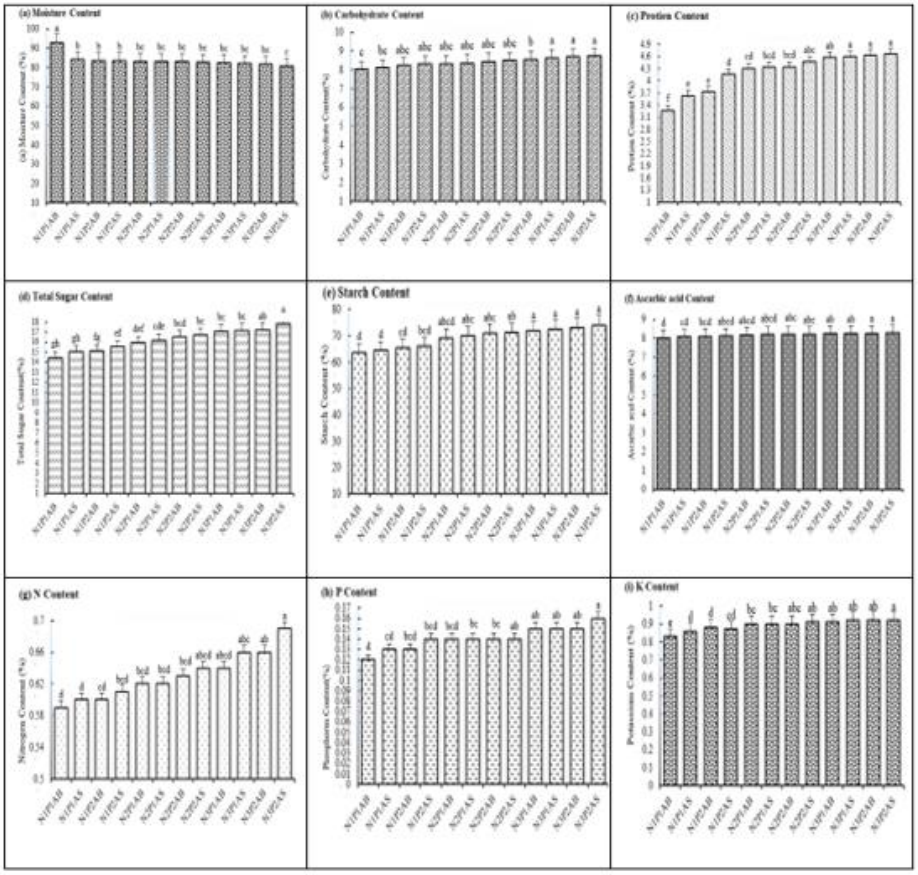

Figure 4. Including Nitrogen (N), Phosphorus (P), Potassium (K), moisture, carbohydrates, protein, total sugar, starch, and ascorbic acid content.

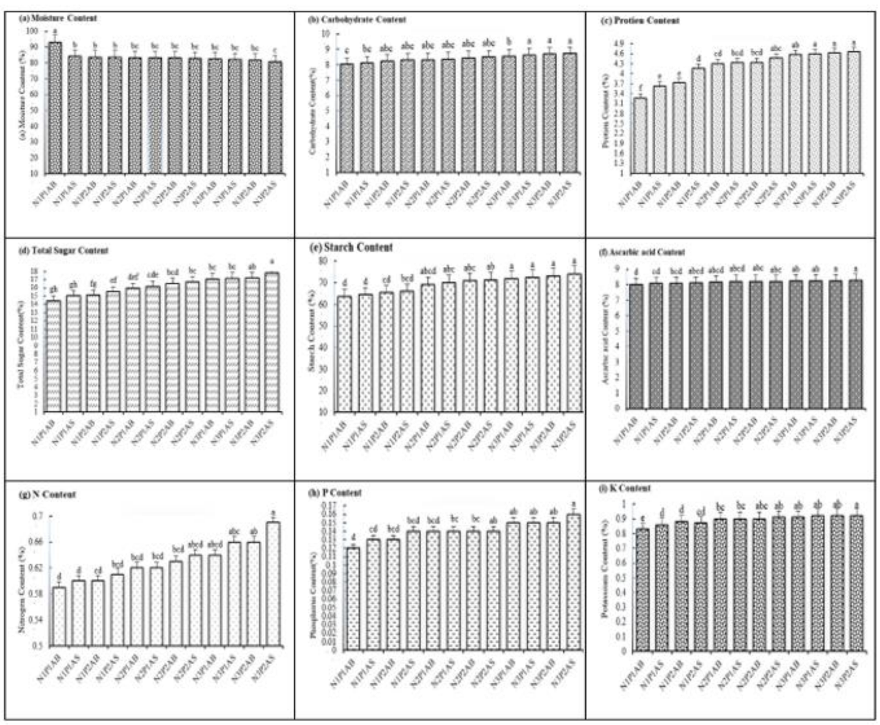

Figure 5. Effect of nitrogen, phosphorous, and bio-fertilizers on the quality of baby corn: (a) Moisture, (b) Carbohydrate, (c) Protein, (d) Total sugar, (e) Starch, (f) Ascorbic acid, and (g-i) NPK contents of baby corn.

Soil properties and available nutrient status

Soil properties: In this investigation, soil pH and organic carbon content (SOC%) were evaluated after the harvest of baby corn to assess the impact of different levels of nitrogen and phosphorus chemical fertilizers in conjunction with various sources of biofertilizers. The results indicated significant variations in soil pH and organic carbon content across the different treatment groups. Specifically, the treatment involving the application of 100 kg ha^{-1} of nitrogen and 75 kg ha^{-1} of phosphorus from chemical fertilizer combined with *Azospirillum* biofertilizer (N3P2AS) recorded the highest levels of soil pH (7.73) and organic carbon (0.47%). In contrast, the treatment labeled as N1P1AB exhibited the lowest values for soil pH (7.27) and organic carbon (0.27%) (Figure 5).

Soil available nutrient status: The nutrient status of the soil was significantly influenced by the application of different doses of nitrogen and phosphorus from chemical fertilizers, combined with various sources of biofertilizers. The study revealed notable effects on soil-available NPK (Nitrogen, Phosphorus, and Potassium) as well as on soil-available micronutrients (zinc, copper, iron, manganese, and sulfur). Specifically, the treatment N3P2AS, which involved applying 100 kg ha^{-1} of nitrogen and 75 kg ha^{-1} of phosphorus from chemical fertilizer along with *Azospirillum* biofertilizer, exhibited higher levels of available NPK (220.43, 31.18, and 283.07 kg ha^{-1}, respectively) compared to other treatments. Conversely, the application of 60 kg ha^{-1} of nitrogen and 50 kg ha^{-1}of phosphorus from chemical fertilizer with *Azotobacter* biofertilizer (N1P1AB) resulted in the lowest available NPK (162.59, 15.54, and 251.68 kg ha^{-1}, respectively). Furthermore, soil-available zinc, copper, iron, manganese, and sulfur were significantly higher in the N3P2AS treatment compared to other treatments. The maximum levels of soil-available zinc, copper, iron, manganese, and sulfur (1.33, 15.11, 16.66, 1.47, and 11.85 ppm, respectively) were observed under the application of 100 kg ha^{-1} of nitrogen and 75 kg ha^{-1} of phosphorus with *Azospirillum* biofertilizer. In contrast, the lowest levels of soil-available micronutrients (0.84, 11.60, 11.81, 1.07, and 11.25 ppm, respectively) were recorded with the application of 60 kg ha^{-1} of nitrogen and 50 kg ha-1 of phosphorus from chemical fertilizer with *Azotobacter* biofertilizer (Figure 6).

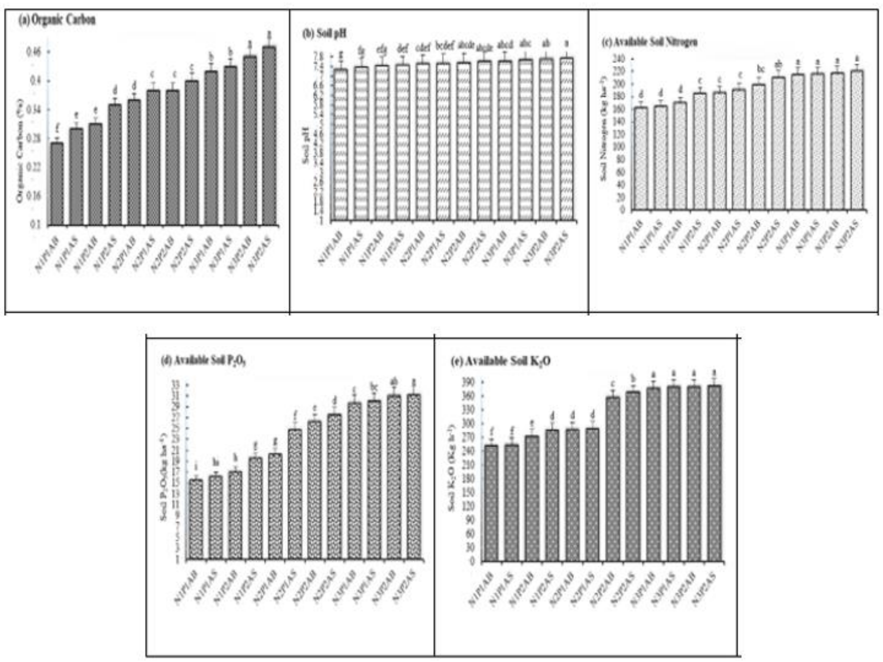

Figure 6. Effect of NP and bio-fertilizers on soil status (a) Organic carbon, (b) pH, (c-e) Macronutrients (N, P, and K) of soil and after harvest of baby corn.

Economics

The economic feasibility of the treatments utilized in this study was evaluated by calculating key financial indicators, including cultivation costs, gross returns, net returns, and benefit-cost ratios (Figure 7). The application of different doses of nitrogen and phosphorus from chemical fertilizers, combined with various sources of biofertilizers, significantly influenced these economic parameters. Notably, among the treatments that employed high doses of chemical fertilizers along with biofertilizers, no significant effect was observed on cultivation costs. However, the treatment N1P1AB incurred the highest cultivation cost, amounting to Rs. 797.9 USD per hectare. From an economic perspective, applying 100 kg of nitrogen and 75 kg of phosphorus per hectare from chemical fertilizers, combined with *Azospirillum* biofertilizer (N3P2AS), emerged as the most financially viable option. This treatment yielded the highest net return of Rs. 2348.3 USD per hectare, along with a notable Benefit-Cost Ratio (BCR) of 2.94. This indicates that for every unit of cost invested in this treatment, farmers can expect to receive a return of 2.94 units of benefit. Furthermore, the application of 60 kg of nitrogen and 50 kg of phosphorus per hectare from chemical fertilizers, combined with *Azotobacter* biofertilizer (N1P1AB), exhibited a respectable BCR of 1.28, accompanied by a net return of Rs. 962.6 USD per hectare, positioning it as the second-best option in terms of economic viability (Figure 8).

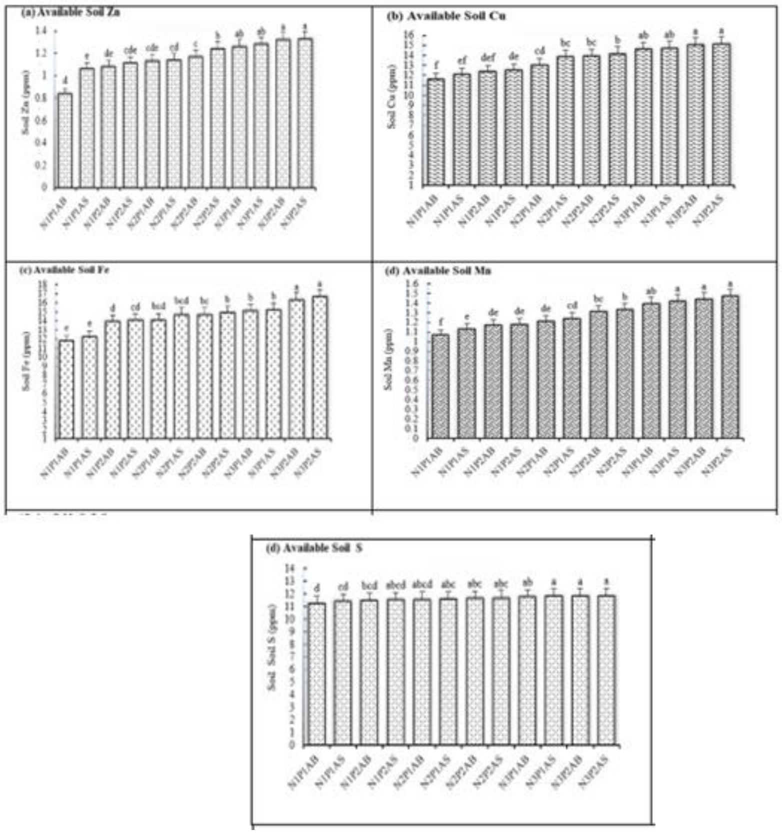

Figure 7. Effect of NP and bio-fertilizers on soil macronutrients (a) Zn, (b) Cu, (c) Fe, (d) Mn, and (e) S of soil and after harvest of baby corn.

Relationships between yield and soil nutrients

Yield attributes such as cob girth, cob length, cob weight, number of cobs, cob yield, and green fodder yield of baby corn exhibited significant improvements with the application of higher levels of nitrogen (100 kg ha^{-1}) and phosphorus (75 kg ha^{-1}). The treatment utilizing 100 kg ha^{-1} nitrogen and 75 kg ha^{-1} phosphorus combined with *Azospirillum* biofertilizer (N3P2AS) consistently outperformed other treatments in terms of yield attributes. The application of N3P2AS demonstrated significant effects on cob girth, with the maximum girth observed compared to other treatments. Similarly, N3P2AS exhibited the greatest cob length. Higher cob weight was evident with the application of N3P2AS, indicating the positive impact of nitrogen and phosphorus in conjunction with *Azospirillum* biofertilizer. Observations also revealed a positive correlation between nitrogen-phosphorus application and the number of cobs per plant, with the N3P2AS treatment resulting in the maximum number of cobs per plant. Moreover, higher cob yield both with and without husk, as well as green fodder yield, were associated with the application of elevated levels of nitrogen and phosphorus, particularly with the N3P2AS treatment. However, the harvest index showed no significant differences among treatments, suggesting that while nutrient application influenced yield attributes, it did not impact the harvest index. Furthermore, soil nutrient analysis indicated that the N3P2AS treatment led to higher levels of available NPK and micronutrients (zinc, copper, iron, manganese, and sulfur) in the soil compared to other treatments. In contrast, the N1P1AB treatment, characterized by lower levels of nitrogen and phosphorus with *Azotobacter* biofertilizer, resulted in comparatively lower levels of available nutrients in the soil. These results highlight a strong positive correlation between the application of higher levels of nitrogen and phosphorus, particularly when combined with *Azospirillum* biofertilizer, and the enhancement of both yield attributes and soil nutrient status.

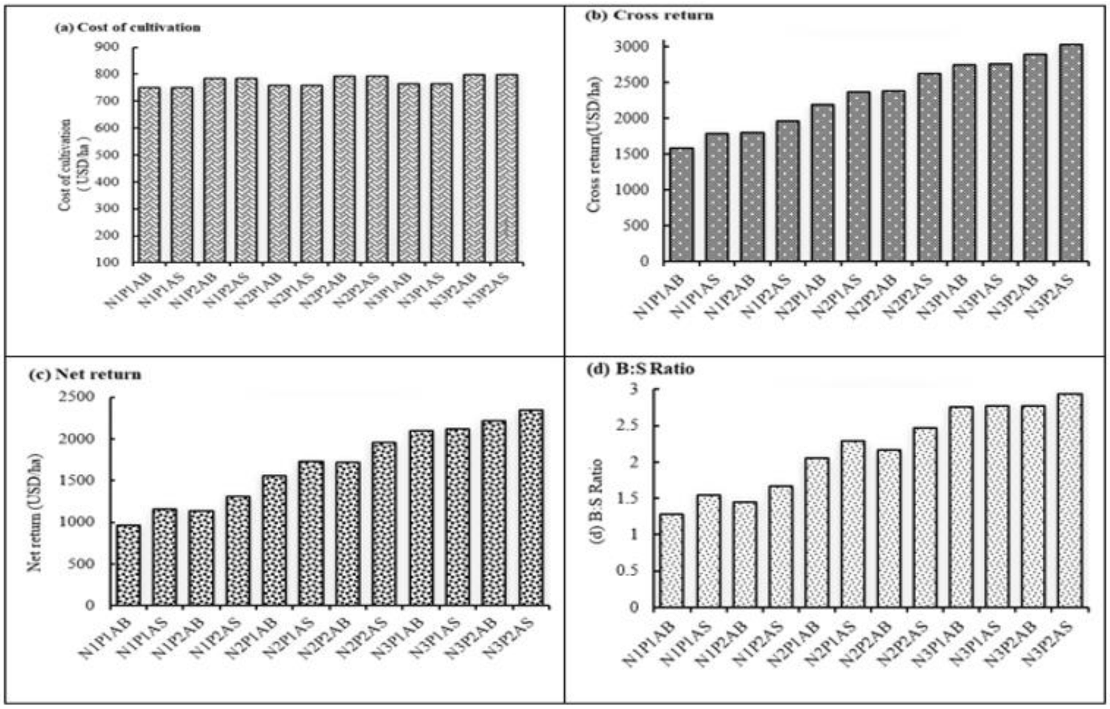

Figure 8. Impact of NP and bio-fertilizers on the economics of baby corn (a) Cost of cultivation, (b) Gross return, (c) Net return, and (d) B: S ratio after harvest.

DISCUSSION

Yield and yield attributes: The findings from our results indicate a significant and positive response in yield attributes, particularly when utilizing 100 kg of Nitrogen per hectare (N ha^{-1}) and 75 kg of phosphorus per hectare (P ha^{-1}) from chemical fertilizers combined with *Azospirillum*. Notably, various parameters such as the number of cobs per plant, cob length, cob girth, cob weight, baby corn yield, green fodder yield, and harvest index demonstrated substantial increases compared to treatments with lower nitrogen and phosphorus levels that used *Azotobacter*. These results suggest that incorporating *Azospirillum* along with higher nitrogen and phosphorus levels (N3P2AS) may lead to increased yields of both baby corn and green fodder. This finding holds particular significance for farmers seeking to enhance crop production and optimize harvest outcomes. Furthermore, our findings align with previous research by Patil et al.; Rao et al.; Kunjir et al.; Muthukumar et al.; Sobhana et al.; and Yakadri et al., which consistently demonstrate the positive impact of *Azospirillum* on yield attributes and overall yield in plants cultivated with higher nitrogen and phosphorus levels. One plausible explanation for this phenomenon is the role of *Azospirillum* in enhancing nutrient availability in the soil. Therefore, based on our findings, we conclude that the application of 100 kg of N ha^{-1} and 75 kg of P ha^{-1} from chemical fertilizers combined with *Azospirillum* can significantly enhance the yield attributes and total yield of baby corn, providing valuable insights for farmers aiming to improve crop production and optimize harvest outcomes. Moreover, our study highlights that among the various yield-related indicators, green fodder yield and baby corn yield exhibited the most significant improvements when combined with 100 kg of N ha^{-1} and 75 kg of P ha^{-1} from chemical fertilizers in conjunction with *Azospirillum*. These results underscore the potential effectiveness of *Azospirillum* when paired with elevated nitrogen and phosphorus levels in promoting the growth and development of baby corn and green fodder, ultimately leading to higher yields.

Quality: The study investigated the impact of different levels of nitrogen and phosphorus, as well as biofertilizers, on the total sugar content and various quality parameters of baby corn, including protein, carbohydrates, starch, ascorbic acid, and NPK content. Figure 3 illustrates that the application of 100 kg ha^{-1} of nitrogen and 75 kg ha^{-1} of phosphorus from chemical fertilizers combined with *Azospirillum* (N3P2AS) resulted in the highest protein and total sugar content, significantly differing from the N1P1AB treatment. Utilizing both chemical and biological fertilizers appeared beneficial for improving soil conditions and supporting root development, proliferation, and functional activation. This positive influence enhanced nutrient absorption by plants, consequently elevating levels of protein, carbohydrates, starch, and total sugars in baby corn. Comparable results were reported by Arunkumar et al. and Suthar et al., highlighting the role of heightened metabolic activity in improving crop quality. Moreover, the concentration of nutrients in baby corn was notably affected by varying levels of chemical fertilizers. The treatment with 100 kg ha^{-1} of nitrogen and 75 kg ha^{-1} of phosphorus combined with *Azospirillum* (N3P2AS) demonstrated the highest Nitrogen (N), Phosphorus (P), and Potassium (K) content, exhibiting a significant difference from the N1P1AB treatment. These findings are consistent with previous research by Verma et al. and Kumar et al., indicating the importance of fertilizer management in optimizing nutrient levels in crops.

Soil properties and available nutrient status: The application of different doses of nitrogen and phosphorus, alongside various biofertilizers, significantly impacted soil pH and Soil Organic Carbon (SOC) levels. Among these treatments, N3P2AS demonstrated notably higher carbon sequestration rates compared to the others, which can be attributed to enhanced root growth and biomass production, resulting in a greater quantity of carbon residues remaining in the soil post-harvest (Babu et al., 2020). This increase in carbon sequestration is likely a consequence of the intensive use of chemical fertilizers under similar conditions, consistent with previous findings. Furthermore, the availability of both macronutrients (NPK) and micronutrients (zinc, copper, iron, manganese, and sulfur) in the soil after baby corn harvest was significantly influenced by the levels of chemical fertilizers and the choice of biofertilizer. A discernible variation in available nitrogen, phosphorus, and potassium was observed with each incremental increase in chemical fertilizer levels, particularly notable with the application of 100 kg ha^{-1} of nitrogen and 75 kg ha^{-1} of phosphorus from chemical fertilizer combined with *Azospirillum* (N3P2AS). This heightened fertility level, along with the chosen biofertilizer, ensured the provision of these essential nutrients in adequate quantities to support crop growth while leaving a substantial portion in the soil after meeting crop demands, thereby enhancing soil fertility. These findings are corroborated by previous studies.

Economics: This underscores the potential efficacy of biofertilizers in enhancing soil fertility and nutrient availability, which ultimately leads to increased crop yields and improved profitability for farmers. Economically, utilizing *Azospirillum* to apply 100 kg ha^{-1} N and 75 kg ha^{-1} P from chemical fertilizers (N3P2AS) resulted in the highest net return of Rs. 2,348.3 USD ha^{-1}, with a Benefit-Cost Ratio (BCR) of 2.94. This indicates that for every unit of cost invested in this treatment, farmers can anticipate a return of 2.94 units of benefit. Applying 60 kg ha^{-1} N and 50 kg ha^{-1} P from chemical fertilizers with *Azotobacter* (N1P1AB) yielded a BCR of 1.28 and a net return of Rs. 962.6 USD ha^{-1}, making it the second-best economic option. These findings suggest that integrating biofertilizers with nitrogen and phosphorus fertilizers, particularly through the use of *Azospirillum* and higher nutrient levels, may enhance profitability for farmers. Additionally, the study observed that higher cob production levels correlated with increased net returns and Benefit-Cost Ratios (BCRs). This highlights the potential for farmers to improve profitability by optimizing fertilization strategies to promote higher cob production. It is crucial for farmers to carefully consider the economic implications of different treatments and to use fertilizers and biofertilizers in a way that maximizes their return on investment. Interestingly, Singh et al. observed similar findings in their research, confirming the importance of cob production levels in determining the economic viability of baby corn cultivation. These insights may be valuable for farmers and agricultural researchers seeking to optimize crop production and enhance profitability.

Effects of different fertilizers on yield, soil, relationships, and economics: The effects of different fertilizers on yield, soil relationships, and economics were thoroughly investigated in this study. The application of high levels of nitrogen (100 kg ha^{-1}) and phosphorus (75 kg ha^{-1}) from chemical fertilizers, combined with *Azospirillum* (N3P2AS), emerged as a pivotal factor in significantly enhancing yield attributes such as cob girth, cob length, cob weight, number of cobs, cob yield, and green fodder yield when compared to other treatments. The notable superiority of N3P2AS in promoting these yield attributes underscores its efficacy in fostering the growth and development of baby corn (Smith et al., 2024). Economic analysis revealed that, despite the higher application costs associated with N3P2AS, it yielded the highest net return per hectare and a remarkable Benefit-Cost Ratio (BCR) of 2.94, indicating substantial profitability. This economic advantage can be attributed to the superior yields and yield attributes achieved with N3P2AS, which more than compensated for the initial investment in fertilizer. Therefore, N3P2AS emerged as the most financially viable option among the evaluated treatments. Moreover, the N3P2AS treatment significantly influenced soil nutrient status, leading to higher levels of available NPK and micronutrients compared to other treatments. The increased availability of essential nutrients in the soil under N3P2AS likely contributed to enhanced plant growth and yield. There is a clear relationship between fertilizer application, yield attributes, and soil nutrient status, with higher levels of nitrogen and phosphorus—particularly with *Azospirillum* biofertilizer (N3P2AS)—positively impacting both yield attributes and soil nutrient availability. This indicates a synergistic relationship between fertilizer application and crop productivity. Consistently, N3P2AS outperformed other treatments in terms of yield, soil nutrient status, and economic viability (Johnson et al., 2024). The combination of high nitrogen and phosphorus levels with *Azospirillum* biofertilizer resulted in superior yield attributes, increased soil nutrient availability, and higher profitability. The higher investment in fertilizer with N3P2AS was justified by the substantial increase in yield and subsequent financial returns, making it the most effective and efficient choice for baby corn cultivation. The multifaceted benefits of N3P2AS in enhancing yield, soil fertility, and economic returns underscore its significance as the optimal fertilizer option for baby corn cultivation.

CONCLUSION

The investigation concludes that integrating biofertilizers, such as *Azotobacter* and *Azospirillum*, alongside nitrogen and phosphorus fertilization, plays a pivotal role in optimizing baby corn output. Notably, *Azospirillum* exerts a significant influence on baby corn production and its associated attributes. The most effective approach among the treatments involved applying 100 kg ha^{-1} of nitrogen and 75 kg ha^{-1} of phosphorus from chemical fertilizers in conjunction with *Azospirillum* (N3P2AS), resulting in increased baby corn yield and elevated levels of protein (4.66%), total sugar (17.86%), carbohydrates (8.73%), starch (74.10%), and ascorbic acid (8.27%). Moreover, this application positively affected soil characteristics, including enhanced pH, organic carbon content, and levels of available macro- and micronutrients, with NPK content increasing by 0.69%, 0.16%, and 0.92%, respectively. These findings suggest that applying chemical nitrogen and phosphorus fertilizers along with biofertilizers significantly enriches the available nitrogen, phosphorus, and potassium, as well as the micronutrient profile of the soil after the baby corn harvest. The economic evaluation underscores the practical implications of the research, revealing that the application of high doses of nitrogen and phosphorus with *Azospirillum* (N^{**} 2AS) yields the highest net return (Rs. 2348.3 USD ha^{-1}) and an exceptional Benefit-Cost Ratio (BCR) of 2.94. These outcomes highlight the economic advantages of integrating *Azospirillum* into nutrient management strategies. The study emphasizes the importance of tailored nutrient management in enhancing baby corn yield and economic gains. These results offer actionable recommendations for farmers to adopt sustainable and economically viable farming practices. By leveraging these insights, farmers can achieve higher yields and economic returns, particularly during periods of increased demand for baby corn, thereby contributing to the overall prosperity of baby corn production. The study illustrates the feasibility of sustaining crop yields through meticulous nutrient management.

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