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Preface

We would like to present, with great pleasure, the volume-12, Issue-5, May 2026 of a scholarly journal, *International Journal of Environmental & Agriculture Research*. This journal is part of the AD Publications series in the field of *Environmental & Agriculture Research Development*, and is devoted to the gamut of Environmental & Agriculture issues, from theoretical aspects to application-dependent studies and the validation of emerging technologies.

This journal was envisioned and founded to represent the growing needs of Environmental & Agriculture as an emerging and increasingly vital field, now widely recognized as an integral part of scientific and technical investigations. Its mission is to become a voice of the Environmental & Agriculture community, addressing researchers and practitioners in below areas.

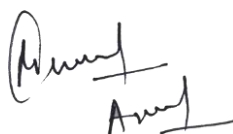
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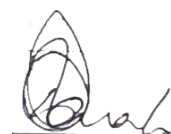
Agriculture, Biological engineering, including genetic engineering, microbiology, Environmental impacts of agriculture, forestry, Food science, Husbandry, Irrigation and water management, Land use, Waste management and all fields related to Agriculture.

Each article in this issue provides an example of a concrete industrial application or a case study of the presented methodology to amplify the impact of the contribution. We are very thankful to everybody within that community who supported the idea of creating a new Research with *IJOEAR*. We are certain that this issue will be followed by many others, reporting new developments in the Environment and Agriculture Research Science field. This issue would not have been possible without the great support of the Reviewer, Editorial Board members and also with our Advisory Board Members, and we would like to express our sincere thanks to all of them. We would also like to express our gratitude to the editorial staff of AD Publications, who supported us at every stage of the project. It is our hope that this fine collection of articles will be a valuable resource for *IJOEAR* readers and will stimulate further research into the vibrant area of Environmental & Agriculture Research.



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Table of Contents

Volume-12, Issue-5, May 2026

S.No	Title	Page No.
1	<p>Effects of Rice Farming Practices and Fertilizer Application on Water Quality of the Mahayahay-Kitcharao Small Reservoir Irrigation Project</p> <p>Authors: Emmalyn E. Montiza; Romell A. Seronay</p> <p> DOI: https://doi.org/10.25125/ijoe-ar-may-2026-1</p> <p> Digital Identification Number: IJOEAR-MAY-2026-1</p>	01-10
2	<p>Economic Assessment of Quality Protein Maize Using Different Plant Geometry and Split Nitrogen Management Strategies</p> <p>Authors: Arju Sahid Ahmed; Partha Sarathi Patra</p> <p> DOI: https://doi.org/10.25125/ijoe-ar-may-2026-2</p> <p> Digital Identification Number: IJOEAR-MAY-2026-2</p>	11-18
3	<p>Valorization of Pomegranate Peel Waste: Extraction of Phenolic-Rich Fractions and Their Antioxidant Performance</p> <p>Authors: Jiayu Liu; Jinhao Jiang; Marwan M. A. Rashed; Han Fangkai; Abduljalil D. S. Ghaleb; Najeeb S. Al-zoreky; Sallah A. Al Hashedi; Ammar AL-Farga</p> <p> DOI: https://doi.org/10.25125/ijoe-ar-may-2026-3</p> <p> Digital Identification Number: IJOEAR-MAY-2026-3</p>	19-30
4	<p>Effect of Different Levels of Neem Coated Urea on Productivity of Finger Millet (<i>Eleusine coracana</i> L. Gaertn)</p> <p>Authors: Kapil Umpo; Sonbeer Chack; Kasinam Doruk; Raja Husain; Masuma Khanan</p> <p> DOI: https://doi.org/10.25125/ijoe-ar-may-2026-4</p> <p> Digital Identification Number: IJOEAR-MAY-2026-4</p>	31-36



Effects of Rice Farming Practices and Fertilizer Application on Water Quality of the Mahayahay-Kitcharao Small Reservoir Irrigation Project

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Abstract— This study examined fertilizer application practices and their association with nutrient concentrations in irrigation water of the Mahayahay–Kitcharao Small Reservoir Irrigation Project (KSRIP) in Agusan del Norte, Philippines, during the dry season. Nitrogen (N), phosphorus (P), and potassium (K) levels were assessed across upstream, midstream, and downstream locations using a descriptive-comparative design integrating survey data from 64 rice farmers and laboratory water analysis. Survey results showed 78.1% of farmers were ≥ 50 years old (mean 56.4 years), with average farming experience of 22.3 years; 79.7% were tenants, and 93.8% used only inorganic fertilizers, applied twice per season via broadcast method. Laboratory analysis revealed N concentrations of 0.0075 mg/L (upstream and midstream) and 0.3317 mg/L (downstream). P ranged from 0.1567 to 0.2800 mg/L, and K from 0.7833 to 0.8167 mg/L. Kruskal–Wallis tests showed no significant differences in N, P, or K among sites ($p > 0.05$). All N and P values were within DENR allowable limits for irrigation water (N: 14 mg/L; P: 1 mg/L). Potassium has no established regulatory standard. Despite intensive uniform fertilizer use, dry-season nutrient concentrations remained within regulatory thresholds without significant spatial variation. Continued monitoring and improved fertilizer management are recommended.

Keywords— irrigation water quality, nutrient accumulation, rice farming practices, fertilizer management, agricultural sustainability.

I. INTRODUCTION

Irrigation development is critical for increasing agricultural productivity and food security in developing countries [1]. In the Philippines, small reservoir irrigation systems stabilize crop production during dry seasons, but their long-term sustainability depends on responsible nutrient management [2]. Excessive or poorly timed fertilizer application can lead to nutrient losses through runoff and leaching, accumulating within irrigation systems [3]. Nitrogen, phosphorus, and potassium—the primary macronutrients in rice cultivation—are particularly concerning when applied in conventional flood-irrigated systems [4].

In Agusan del Norte, the Kitcharao Small Reservoir Irrigation Project (KSRIP) supplies irrigation water to approximately 550 hectares of farmland. As fertilizer use intensifies to meet production targets, assessing whether nutrient concentrations remain within regulatory limits (DENR Administrative Order 2016-08 and 2021-19 for Class C fresh surface waters) becomes essential. Dry-season conditions with reduced water volume may concentrate nutrients, potentially creating spatial differences among upstream, midstream, and downstream sections.

This study examines fertilizer application practices and their relationship to N, P, and K concentrations in irrigation water within the Mahayahay-KSRIP during the dry season, comparing spatial patterns and assessing compliance with national

standards. It was hypothesized that nutrient concentrations would increase progressively from upstream to downstream locations due to cumulative fertilizer inputs.

II. MATERIALS AND METHODS

2.1 Research Design and Locale:

A descriptive-comparative design was employed. The study was conducted in Kitcharao, Agusan del Norte, Philippines (fourth-class municipality, agriculture-dependent economy), focusing on the Mahayahay-KSRIP during the dry season.

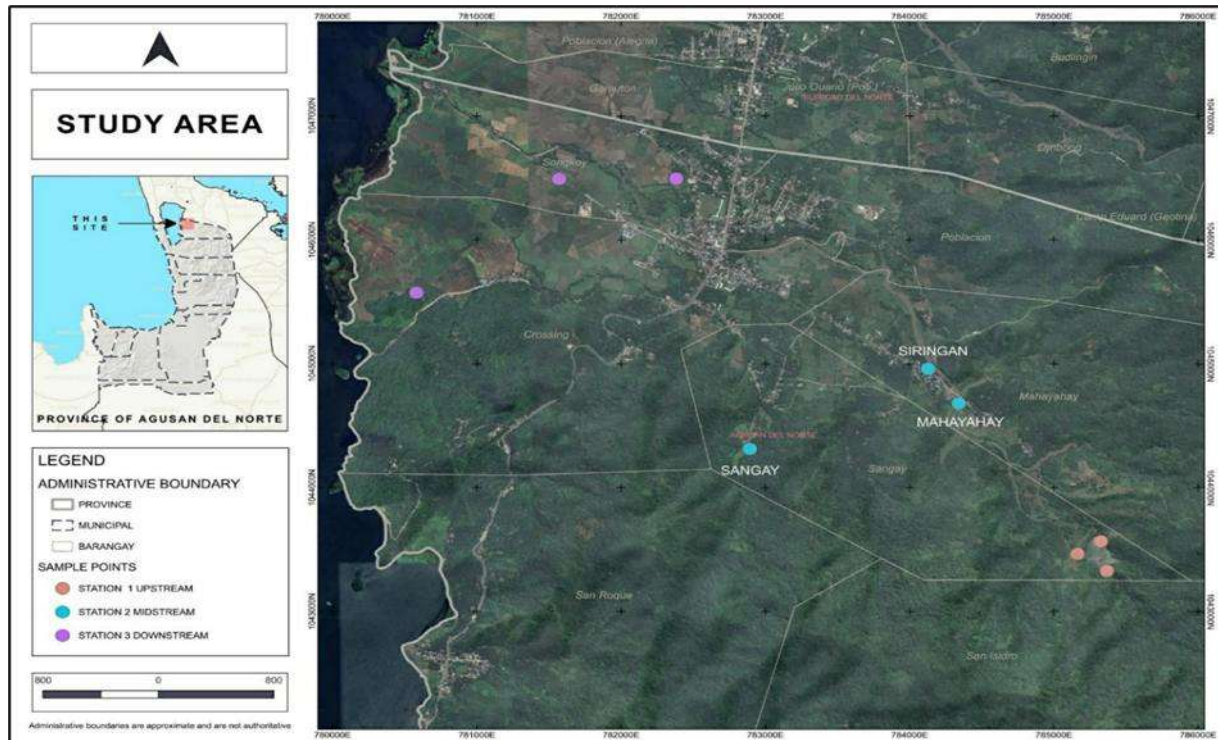


FIGURE 1: Location map of the study area

2.2 Participants and Sampling:

Sixty-four rice farmers actively cultivating within the irrigation service area were selected via convenience sampling. Inclusion criteria: residing within 2 km of the reservoir and farming with any fertilizer type.

2.3 Survey Instrument:

A structured questionnaire (face-to-face interviews, KoBoCollect mobile app) collected: (a) demographics (age, sex, education, land ownership, farm size, experience, location); (b) fertilizer practices (type, frequency, method, water source); (c) perceptions of water quality (5-point Likert scales). The questionnaire was validated by experts and pilot-tested (n=10).

2.4 Water Sampling and Laboratory Analysis:

Water samples were collected from three stations (upstream, midstream, downstream; ~1 km apart) during the dry season. Three replicate samples per station were taken every 2 hours, stored in insulated containers with ice, and transported to an accredited laboratory. Analytical methods: Nitrogen (Devarda Alloy Method), Phosphorus (Vanadomolybdate Method), Potassium (ICP-OES). Detection limits: N=0.015 mg/L; P=0.01–0.017 mg/L. Values below detection limit (BDL) were substituted with half the limit [5].

2.5 Data Analysis:

Descriptive statistics (frequencies, means, SD) characterized demographics and fertilizer practices. Chi-square tests (or Fisher's exact) assessed associations between location and fertilizer practices ($\alpha=0.05$). Kruskal–Wallis test compared nutrient concentrations across locations due to non-normal distribution and small sample size. Effect sizes: Cramér's V (chi-square) and eta-squared (η^2). Analyses used SPSS.

2.6 Regulatory Benchmark:

Measured concentrations were compared with DENR DAO 2016-08/2021-19 Class C standards for irrigation water: Nitrate (as NO₃-N) ≤14 mg/L; Phosphate (as PO₄) ≤1 mg/L; no standard for potassium.

III. RESULTS

3.1 Demographic Characteristics of Rice Farmers:

The demographic profile of rice farmers within the Mahayahay–Kitcharao Small Reservoir Irrigation Project (KSRIP) reveals a predominantly aging farming population. As shown in Table 1, 78.1% of respondents were 50 years of age or older, with a mean age of 56.4 years (SD = 8.7). Only 4.7% belonged to the 30–39 age cohort, indicating limited participation by younger generations in rice farming activities. This age distribution is consistent with national trends in Philippine agriculture, where outmigration of youth to urban centers has left an aging workforce in rural areas [6]. The near-equal sex distribution (51.6% male, 48.4% female) highlights the significant but often underrecognized role of women in rice production, particularly in labor-intensive activities such as transplanting, weeding, and fertilizer application [7].

Educational attainment among respondents was generally low: 42.2% completed only elementary education, 48.4% reached high school, and only 7.8% attended college. Limited formal education may influence farmers' decision-making processes regarding fertilizer selection, dosage, and timing, often leading to reliance on traditional practices or imitating neighbors rather than evidence-based nutrient management [8].

Land tenure status further contextualizes farming behavior. The majority of farmers (79.7%) were either tenants (42.2%) or renters (37.5%), with only 20.3% owning the land they cultivated. This predominance of tenancy arrangements may discourage long-term investments in soil and nutrient management, as the benefits of such investments often accrue to landowners rather than to tenants. Consequently, tenant farmers may prioritize short-term yield gains through intensive inorganic fertilizer use rather than adopting more sustainable but potentially costlier practices [9].

Farm size averaged 1.2 hectares (SD = 0.9), ranging from 0.25 to 5 hectares, confirming that farming operations are small-scale—typical of irrigated rice systems in the Philippines [10]. Mean farming experience was 22.3 years (SD = 10.2), with nearly 80% of respondents having more than a decade of experience. Such extensive experience suggests that current farming practices are deeply entrenched and may be resistant to change, even when alternative nutrient management strategies offer environmental benefits [11]. In terms of spatial distribution within the irrigation system, 48.4% of farms were located downstream, 31.3% midstream, and 20.3% upstream. This downstream concentration is particularly relevant because downstream sections of irrigation networks typically receive cumulative agricultural runoff and drainage from upstream areas, potentially influencing observed nutrient patterns [12].

**TABLE 1
 DEMOGRAPHIC PROFILE OF THE RESPONDENTS**

Variable	Category	Frequency	Percentage (%)
Age (years)	30–39	3	4.7
	40–49	11	17.2
	50–59	26	40.6
	60 and above	24	37.5
	Total	64	100
Sex	Male	33	51.6
	Female	31	48.4
	Total	64	100
Educational Level	Elementary	27	42.2
	High School	31	48.4
	College	5	7.8
	Post-Baccalaureate	1	1.6
Total		64	100

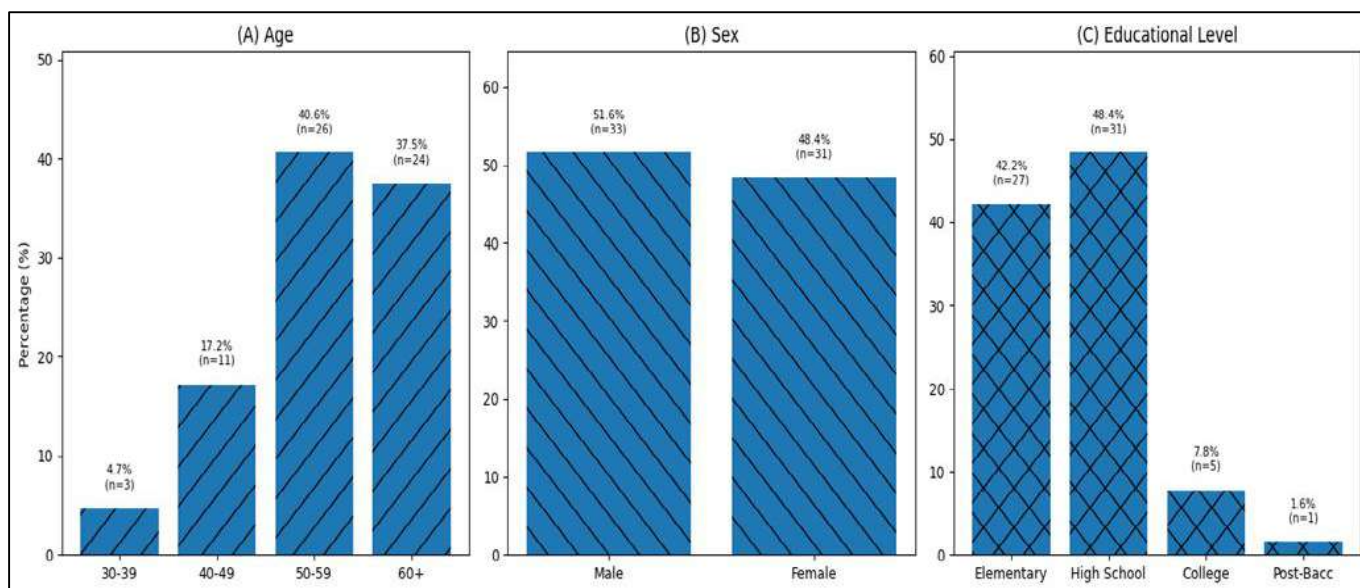


FIGURE 2: Distribution of respondents' demographic profile in terms of age, sex, and educational level

3.2 Fertilizer Application Practices:

Fertilizer application practices were remarkably uniform across all three spatial locations, indicating a standardized approach to nutrient management among farmers in the irrigation service area. Table 2 summarizes these practices. The vast majority of respondents (93.8%) relied exclusively on inorganic (chemical) fertilizers, with only 1.6% using organic fertilizers alone and 4.7% employing a combination of organic and inorganic inputs. The minimal adoption of organic or integrated nutrient management reflects a strong preference for readily available, fast-acting chemical fertilizers that provide immediate visual yield responses [8,11]. Statistical analysis using the chi-square test revealed no significant association between farm location and fertilizer type ($\chi^2 = 3.669$, $df = 4$, $p = 0.453$), confirming that fertilizer choice is spatially homogeneous throughout the irrigation system. This uniformity implies that any observed spatial variation in nutrient concentrations is unlikely to be driven by differences in fertilizer type and must instead be explained by hydrological transport processes or other environmental factors [13].

Regarding application frequency, 89.1% of farmers applied fertilizers twice per cropping season, 9.4% applied once, and only 1.6% applied more than twice. The mean number of applications per season was 1.92. This twice-per-season schedule aligns with recommended nutrient management guidelines for irrigated rice during the dry season, where split applications are designed to synchronize nutrient availability with critical crop growth stages—typically at transplanting or early tillering and again at panicle initiation [11]. However, the slight variation observed in the downstream section (16.1% applying once per season, 80.7% twice, and 3.2% more than twice) was not statistically significant ($\chi^2 = 4.959$, $df = 4$, $p = 0.292$). Nevertheless, even small differences in application timing can influence downstream nutrient transport in gravity-fed irrigation networks, as water flowing from upstream to downstream fields may carry dissolved or suspended nutrients from earlier applications [13].

All farmers (100%) reported using the broadcast method for fertilizer application, where granules are manually scattered over the flooded rice field surface. While broadcast application is labor-efficient and requires no specialized equipment, it is associated with lower nutrient use efficiency compared to deep placement or split-band methods. In flooded rice systems, broadcast-applied nitrogen, particularly urea, is susceptible to volatilization losses, while phosphorus may be fixed in soil or lost with surface runoff [14]. Furthermore, all farmers depended exclusively on the small reservoir (dam) as their sole source of irrigation water. This reliance means that water is recirculated within the system, and any nutrients not taken up by crops can remain in the irrigation network and be transported downstream. The combination of broadcast application, exclusive reservoir water use, and gravity-fed flow creates conditions conducive to the redistribution of nutrients within the irrigation system, making spatial monitoring particularly important.

TABLE 2
FERTILIZER TYPE USAGE BY LOCATION IN THE IRRIGATION SYSTEM

Location	Inorganic Only	Organic Only	Combination	Total
Upstream	13 (100.0%)	0 (0.0%)	0 (0.0%)	13
Midstream	18 (90.0%)	1 (5.0%)	1 (5.0%)	20
Downstream	29 (93.5%)	0 (0.0%)	2 (6.5%)	31
Total	60 (93.8%)	1 (1.6%)	3 (4.7%)	64

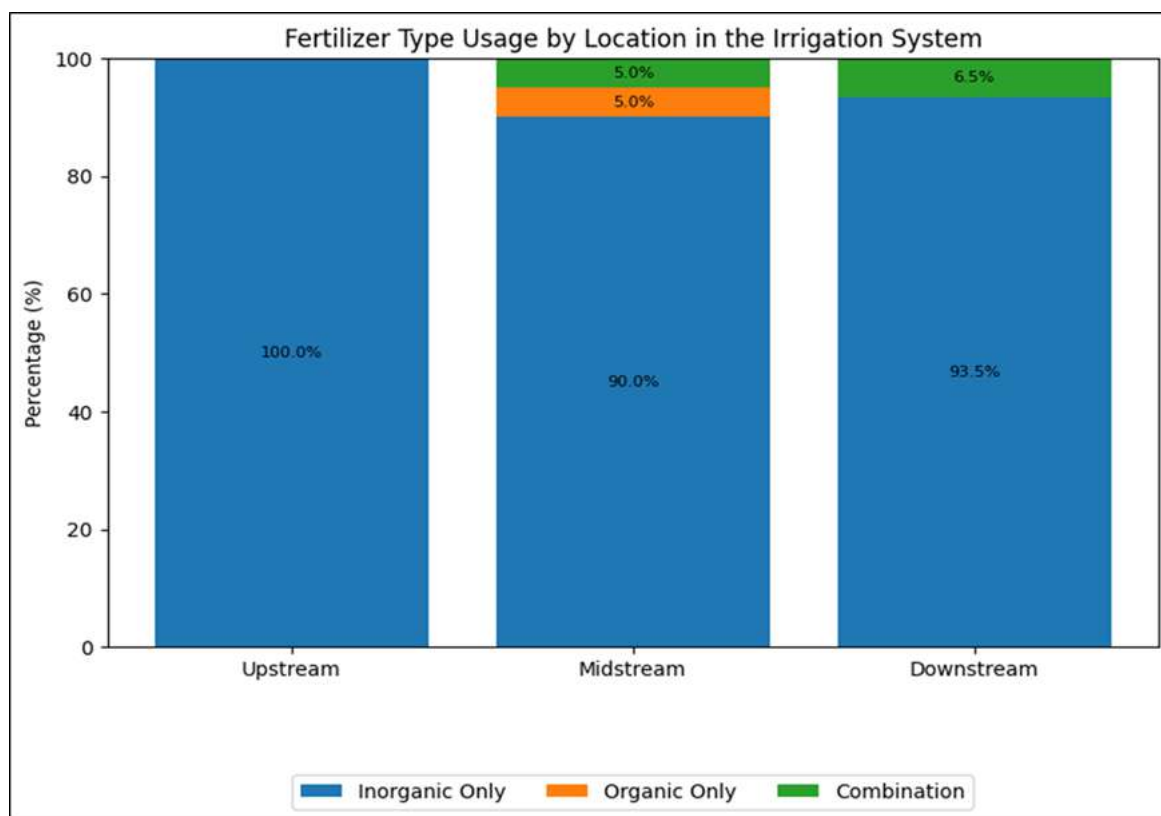


FIGURE 3: Distribution of fertilizer type usage across irrigation system locations

3.3 Nutrient Concentrations Across Locations:

Table 3 presents the mean concentrations of nitrogen (N), phosphorus (P), and potassium (K) measured at upstream, midstream, and downstream sampling locations during the dry season. Each location was sampled in triplicate (n = 3 per location). Nitrogen concentrations were identical and minimal at upstream and midstream locations (0.0075 mg/L), which corresponds to half of the laboratory detection limit (BDL substitution). The presence of BDL values upstream and midstream suggests that nitrogen inputs from fertilizer applications in these upper sections were either rapidly taken up by crops, lost to the atmosphere via volatilization, or not yet transported at the time of sampling. In contrast, the downstream location showed a substantially higher mean nitrogen concentration of 0.3317 mg/L, with individual sample values ranging from below detection (0.0075 mg/L) to 0.98 mg/L. This nearly 44-fold increase in mean concentration from upstream to downstream (0.0075 → 0.3317 mg/L) is descriptively notable, suggesting a potential accumulation trend. One possible explanation is that nitrogen—particularly in nitrate form—is highly mobile in water and can be transported from upstream and midstream fields to downstream sections through irrigation flow and field drainage [3,13]. However, the large standard deviation downstream (SD = 0.5615) indicates high variability among replicate samples, which may reflect intermittent transport processes or localized input events.

Phosphorus concentrations showed moderate variability without a consistent spatial trend. The highest mean concentration was observed downstream (0.2800 mg/L), followed by upstream (0.2533 mg/L) and midstream (0.1567 mg/L). The midstream location recorded the lowest minimum value (0.01 mg/L), while both midstream and downstream had maximum values of 0.36 mg/L and 0.82 mg/L, respectively. Phosphorus is generally less mobile than nitrogen in soil-water systems because it tends to adsorb to soil particles and is transported primarily with sediment rather than in dissolved form [13]. Therefore, the presence

of phosphorus in irrigation water may be more closely associated with soil erosion or suspended solids rather than direct leaching. The lack of a clear spatial gradient suggests that phosphorus transport is patchy and influenced by local factors such as field slope, soil texture, and recent tillage or irrigation events.

Potassium concentrations remained relatively stable across all three locations: upstream (0.7833 mg/L), midstream (0.8167 mg/L), and downstream (0.8100 mg/L). The coefficients of variation were moderate upstream (25.1%) and midstream (28.8%) but very low downstream (5.7%), indicating that potassium distribution was most uniform in the lower section of the irrigation system. Potassium is known to be less susceptible to leaching compared to nitrogen because it is retained by cation exchange sites in soil [11]. The stability of potassium concentrations across locations suggests that fertilizer-derived potassium is either efficiently taken up by crops or retained within soil profiles, with minimal transport through irrigation water.

Importantly, when compared with the regulatory standards established by the Philippine Department of Environment and Natural Resources (DENR) for Class C fresh surface waters designated for irrigation (DENR Administrative Order 2016-08 and 2021-19), all measured nutrient concentrations were well within allowable limits. The DENR maximum allowable limit for nitrate (as NO₃-N) is 14 mg/L—approximately 42 times higher than the highest observed nitrogen concentration (0.98 mg/L downstream). Similarly, the DENR limit for phosphate (as PO₄) is 1 mg/L, which exceeds all measured phosphorus values. Potassium has no specific regulatory threshold for irrigation water. Therefore, from a regulatory perspective, the irrigation water quality during the dry-season sampling period remained acceptable for agricultural use.

TABLE 3
DESCRIPTIVE STATISTICS OF NUTRIENT CONCENTRATIONS BY LOCATION (MG/L)

Location	Nutrient	n	Mean	SD	Minimum	Maximum
Upstream	Nitrogen	3	0.0075	0	0.0075	0.0075
	Phosphorus	3	0.2533	0.1361	0.1	0.36
	Potassium	3	0.7833	0.1966	0.56	0.93
Midstream	Nitrogen	3	0.0075	0	0.0075	0.0075
	Phosphorus	3	0.1567	0.1818	0.01	0.36
	Potassium	3	0.8167	0.2354	0.59	1.06
Downstream	Nitrogen	3	0.3317	0.5615	0.0075	0.98
	Phosphorus	3	0.28	0.4677	0.01	0.82
	Potassium	3	0.81	0.0458	0.76	0.85

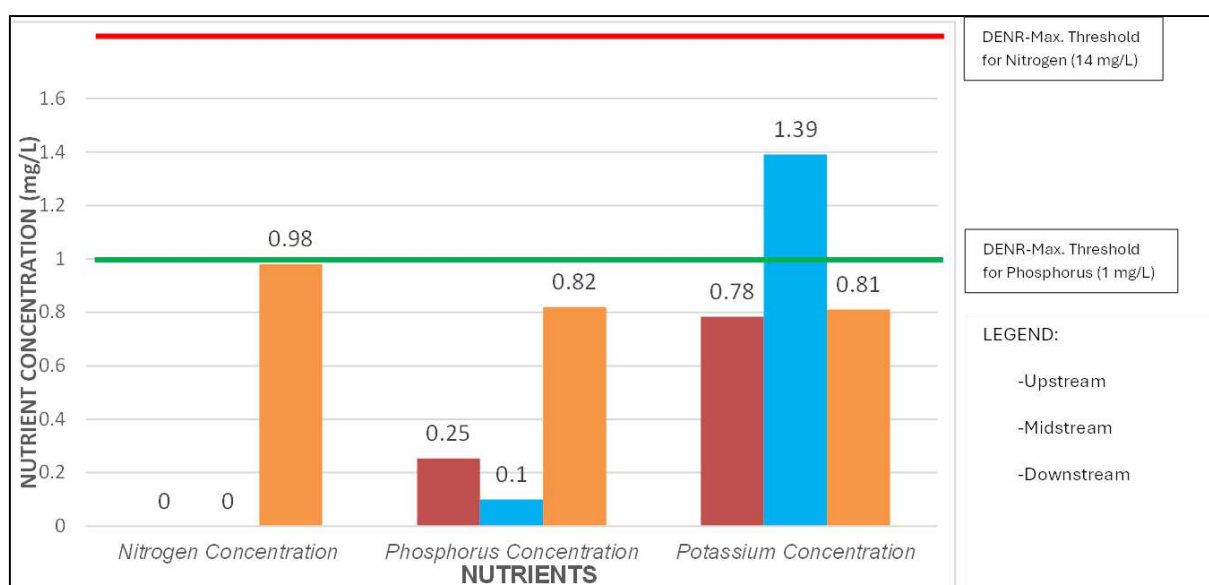


FIGURE 4: Spatial Comparison of N, P, and K Concentrations in Irrigation Water with DENR Regulatory Thresholds

3.4 Statistical Comparison of Nutrient Concentrations:

To determine whether the observed descriptive differences in nutrient concentrations among upstream, midstream, and downstream locations were statistically significant, the Kruskal–Wallis test was employed. This non-parametric test was chosen because of the small sample size ($n = 3$ per location) and the non-normal distribution of nutrient data, as evidenced by the presence of BDL values and high variance in some groups. Table 4 presents the results.

For nitrogen, the Kruskal–Wallis H statistic was 2.000 with 2 degrees of freedom, yielding a p-value of 0.368. Since this p-value exceeds the conventional significance level of $\alpha = 0.05$, the null hypothesis of no difference in nitrogen concentrations among the three locations cannot be rejected. In other words, despite the descriptive 44-fold increase in mean concentration from upstream to downstream, the difference was not statistically significant given the current sample size and data variability. For phosphorus, the H statistic was 0.655 ($df = 2, p = 0.721$), and for potassium, the H statistic was 0.089 ($df = 2, p = 0.957$). Both p-values were substantially above 0.05, indicating no statistically significant differences in phosphorus or potassium concentrations across locations.

The absence of statistical significance does not necessarily mean that no spatial pattern exists. Rather, it suggests that with only three replicate samples per location and the high within-location variability (particularly for nitrogen and phosphorus downstream), the study had limited statistical power to detect small-to-moderate differences. As noted by Egbueri et al. [15], descriptive spatial trends in small irrigation systems may only become statistically detectable after prolonged monitoring or increased sampling frequency. Therefore, while the current results indicate statistical uniformity, the descriptive pattern—especially the downstream nitrogen increase—warrants continued observation with a larger and more temporally replicated sampling design.

Effect sizes were also considered. For the non-significant Kruskal–Wallis tests, eta-squared (η^2) values were small ($\eta^2 < 0.05$ for all nutrients), indicating that location explained very little of the total variance in nutrient concentrations. This reinforces the conclusion that, during the dry-season sampling period, spatial location within the irrigation system was not a meaningful predictor of nutrient levels.

TABLE 4
KRUSKAL–WALLIS TEST RESULTS FOR NUTRIENT CONCENTRATIONS BY LOCATION

Nutrient	H Statistic	df	p-value	Decision
Nitrogen	2	2	0.368	Not Significant
Phosphorus	0.655	2	0.721	Not Significant
Potassium	0.089	2	0.957	Not Significant

3.5 Farmers' Perceptions of Water Quality:

Farmers' perceptions of irrigation water quality were assessed using a five-point Likert scale, with results summarized in Table 5. The overall mean perception score was 3.81 ($SD = 0.42$), corresponding to a verbal interpretation of "Good" and a qualitative rating of "High" (based on the scale where 3.41–4.20 = Good/High). This indicates that, on average, farmers considered the irrigation water suitable for agricultural purposes.

When asked specifically about observable changes in water quality associated with fertilizer use, the mean score was 3.72, suggesting that farmers do recognize some degree of water quality alteration linked to their nutrient management practices. Commonly cited observations included occasional greenish coloration of water (suggesting possible algal growth), turbidity after heavy irrigation events, and a perceived "fertilizer smell" in drainage canals. However, these perceptions were not uniform across all respondents; downstream farmers were more likely to report visible changes than upstream farmers, which aligns with the descriptive increase in nitrogen concentration observed downstream.

Regarding the statement "Fertilizer application has affected the quality of irrigation water," the mean score was 3.68, reflecting moderate agreement. This suggests that while farmers acknowledge a connection between their practices and water quality,

they do not perceive the impact as severe. Importantly, when asked whether water quality changes have affected crop health or yield, the mean score dropped to 3.45, indicating that farmers believe any water quality alterations have had only minor or inconsistent effects on their agricultural productivity.

The convergence between farmers' perceptions (generally good water quality) and laboratory measurements (nutrient levels within regulatory limits) is notable. However, perceptual data should be interpreted with caution, as farmers may not detect subtle nutrient increases that do not produce visible symptoms such as algal blooms, fish kills, or crop damage [16]. Furthermore, the "shifting baseline syndrome" [17] may operate in this community: farmers who have used the irrigation system for decades may perceive current water quality as normal compared to past conditions, even if gradual nutrient enrichment has occurred. Therefore, while perception data provide valuable contextual insight, they should complement rather than replace empirical monitoring.

TABLE 5
FARMERS' FERTILIZER USAGE PRACTICES

Statement	Mean	Interpretation
Regular use of chemical fertilizers	3.98	High
Preference for organic fertilizers	3.16	Moderate
Application follows guidelines	4	High
Mixing fertilizers for yield	3.94	High
Training on fertilizer application	3.95	High
Overall Mean	3.81	High

IV. DISCUSSION

The demographic profile of farmers (aging, low formal education, predominantly tenants) aligns with national trends in Philippine agriculture [6,7] and may influence fertilizer decisions, favoring conventional inorganic inputs over integrated nutrient management [8]. The near-universal reliance on inorganic fertilizers (93.8%) and broadcast application, combined with sole dependence on reservoir irrigation, creates conditions where unabsorbed nutrients can be transported within the irrigation network [3,9].

Despite intensive and uniform fertilizer practices, nutrient concentrations did not differ significantly across upstream, midstream, and downstream locations. This spatial uniformity may be attributed to: (a) relatively short distance between sampling points (~2 km total), limiting cumulative nutrient enrichment; (b) dry-season water management practices that may reduce runoff connectivity; (c) the small reservoir acting as a buffer or mixing zone. However, the descriptive increase in downstream nitrogen (0.0075 → 0.3317 mg/L), though not statistically significant with current sample size (n=3 per location), suggests a potential accumulation trend that warrants further investigation with larger replication [10].

All measured N and P concentrations were well within DENR Class C standards for irrigation water (N: 14 mg/L; P: 1 mg/L), indicating that current fertilizer practices, as of the dry-season sampling, have not caused regulatory exceedances. Potassium levels, for which no standard exists, were stable. These findings are consistent with studies in other irrigated rice systems where nutrient concentrations remained below thresholds under moderate fertilizer inputs [11,12].

Farmers' perception that water quality is "Good" (mean 3.81/5) aligns with laboratory results, though perceptual data should be interpreted cautiously as farmers may not detect subtle nutrient changes [13]. The contrast between observed downstream nitrogen increase (descriptive) and non-significant statistical difference highlights the need for larger sample sizes and seasonal monitoring to detect emerging trends.

V. CONCLUSION

Rice farming in the Mahayahay-KSRIP is characterized by experienced, older, smallholder tenants who rely uniformly on inorganic fertilizers applied twice per season via broadcast method. During the dry-season sampling period, nitrogen, phosphorus, and potassium concentrations did not differ significantly among upstream, midstream, and downstream locations,

and all measured N and P levels complied with DENR irrigation water standards. Therefore, the null hypothesis of no significant difference in nutrient concentrations across locations could not be rejected for any of the three nutrients. Although a descriptive increase in downstream nitrogen was observed, it was not statistically significant. The absence of spatial differentiation suggests that current fertilizer practices have not led to measurable nutrient accumulation within the irrigation network under dry-season conditions. However, continued monitoring is essential to detect potential long-term changes. Current fertilizer practices, under dry-season conditions, do not appear to cause regulatory exceedances, but continued monitoring is warranted.

VI. RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed.

First, regular seasonal monitoring of nitrogen, phosphorus, and potassium should be conducted during both dry and wet seasons to capture temporal variations in nutrient concentrations, as the current study was limited to dry-season sampling only.

Second, the sampling design should be strengthened by increasing the number of replicates and sampling sites to improve statistical power and enable detection of subtle but meaningful spatial differences in nutrient distribution.

Third, agricultural extension services should promote efficient fertilizer management practices among farmers, particularly split-timed application and avoidance of broadcast application before heavy irrigation events, to reduce nutrient runoff while maintaining crop yields.

Fourth, farmers should be encouraged to adopt integrated nutrient management approaches that combine inorganic fertilizers with organic amendments such as compost or rice straw, as this can improve soil nutrient retention and reduce reliance on chemical inputs.

Fifth, continuous farmer education programs should be implemented to raise awareness of DENR water quality standards and the environmental consequences of excessive fertilizer use, using participatory methods tailored to farmers' low formal education levels.

Sixth, collaboration among farmers, the National Irrigation Administration, and the municipal government should be formalized to establish a community-based water quality monitoring program, ensuring sustained data collection and shared accountability.

Finally, further research should examine nutrient dynamics across multiple cropping seasons and include additional water quality parameters such as dissolved oxygen and turbidity to provide a more comprehensive environmental assessment.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this research paper.

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Economic Assessment of Quality Protein Maize Using Different Plant Geometry and Split Nitrogen Management Strategies

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Abstract— A field experiment was conducted during the rabi season (November-April) of 2021-22 and 2022-23 at the instructional farm of Uttar Banga Krishi Viswavidyalaya, West Bengal, aimed at evaluating the effects of plant geometry and split nitrogen management on the economic performance of Quality Protein Maize (*Zea mays* L.). The experimental setup employed a split-plot design with three main plot treatments for plant geometry and five sub-plot treatments for split nitrogen management, with each treatment replicated three times. The main plot treatments included three planting densities and sub-plot treatments contained five different split nitrogen management regimes. Results indicated that among the plant geometry treatments, the PG3 (40 x 20 cm spacing with 125,000 plants ha⁻¹) resulted in the highest cost of cultivation (78,081.49 and 80,865.09 Rs. ha⁻¹), but also achieved the highest gross returns (226,267.9 and 221,563.1 Rs. ha⁻¹), net returns (148,186.38 and 140,998.04 Rs. ha⁻¹), and benefit-cost ratios (2.90 and 2.75) over both years. In contrast, PG1 (60 x 30 cm spacing, 55,555 plants ha⁻¹) showed the lowest economic values, with a cost of cultivation of 73,681.49 and 76,165.09 Rs. ha⁻¹, gross returns of 145,736.7 and 143,451.8 Rs. ha⁻¹, net returns of 72,055.18 and 67,286.66 Rs. ha⁻¹, and a benefit-cost ratio of 1.98 and 1.88 during both years of experimentation. For nitrogen management, the SN5 treatment (10% at basal, 20% at V8, 40% at VT, and 30% at R1) led to significantly higher economic returns, recording gross returns of 193,258.8 and 187,730.6 Rs. ha⁻¹, net returns of 116,961.9 and 108,936.2 Rs. ha⁻¹, and benefit-cost ratios of 2.54 and 2.37. Conversely, the conventional nitrogen management (SN1) yielded the lowest economic outcomes, with gross returns of 173,216.5 and 169,693.3 Rs. ha⁻¹, net returns of 100,329.6 and 94,378.91 Rs. ha⁻¹, and benefit-cost ratios of 2.31 and 2.22 across both years.

The study shows that cultivating Quality Protein Maize (QPM) with the VL QPM Hybrid 59, using a dense planting geometry of 40 x 20 cm (125,000 plants ha⁻¹), significantly enhances economic returns for farmers in North Bengal. This setup optimizes land use and productivity. Additionally, a strategic split nitrogen application (10% basal, 20% at V8, 40% at VT, and 30% at R1) aligns nitrogen availability with key growth stages, promoting optimal growth and yield. Together, these practices present an effective agronomic strategy to improve the profitability of maize farming in the region.

Keywords— quality protein maize, plant geometry, split nitrogen application, economics.

I. INTRODUCTION

Maize (*Zea mays* L.) is recognized as one of the most essential cereal crops worldwide, contributing significantly to food security, particularly in developing regions where it serves as a dietary staple. In India, maize holds a vital place as the third most important crop after rice and wheat, forming a core part of the national diet. However, conventional maize varieties are deficient in certain key amino acids, particularly lysine and tryptophan. These amino acids are fundamental for the synthesis of high-quality proteins in the human body. Due to this deficiency, the protein quality of traditional maize is relatively low, which can lead to malnutrition and a decrease in the biological value of the food, as the net protein utilization in the body is compromised. Consequently, this limitation impacts overall nutritional outcomes, particularly in populations that rely heavily on maize as a primary food source.

Quality Protein Maize (QPM) closely resembles traditional maize in appearance, taste, and grain texture, yet it offers a substantial improvement in nutritional content. Unlike standard maize, QPM contains nearly double the amounts of lysine (approximately 4%) and tryptophan (around 0.8%), two essential amino acids that enhance protein quality and availability. This increased amino acid concentration raises the biological value of QPM, meaning that the proteins it provides are more easily absorbed and utilized by humans and animals alike (Jena et al., 2013). Besides its nutritional benefits, QPM demonstrates a high potential for yields and is naturally resilient against various biotic stresses (like pests and diseases) and abiotic stresses (such as drought and poor soil conditions). With its improved protein profile and adaptability to conventional cultivation methods, QPM offers an affordable and practical protein source that fits seamlessly into existing farming systems. It holds particular promise as a sustainable food option in regions that rely on maize as a dietary staple, addressing protein deficiencies without requiring major changes to agricultural or dietary practices.

Achieving and maintaining an optimal plant population is essential for maximizing the capture of solar radiation, which directly supports photosynthesis and helps crops make the most of available soil resources, such as nutrients and moisture. When the number of plants per unit area surpasses the ideal density, it leads to intense competition both between and within individual plants. This excessive competition limits each plant's access to vital resources, including sunlight, water, and essential nutrients. Furthermore, high plant densities increase the likelihood of crop lodging, where plants bend or fall over, often due to weakened stems, making harvesting more challenging and reducing yield. Thus, establishing the ideal plant density is crucial not only for achieving high grain yields but also for promoting enhanced protein quality in crops. By optimizing plant spacing, farmers can better support crop health, resilience, and productivity, ultimately contributing to more sustainable and efficient agricultural practices.

Nitrogen plays a crucial role in driving yield outcomes in maize production, as it is a fundamental nutrient that supports various aspects of plant growth and development. When nitrogen levels in the soil are inadequate, plants suffer from reduced leaf area, which limits their ability to capture sunlight effectively, thereby lowering photosynthesis rates. This deficiency also hampers overall growth and slows down developmental stages, ultimately resulting in significantly reduced crop yields. On the other hand, excessive nitrogen use, while potentially boosting yields in the short term, comes with several drawbacks. High nitrogen applications increase production costs for farmers and pose environmental risks, as surplus nitrogen can leach into groundwater or volatilize into the atmosphere as nitrous oxide, a potent greenhouse gas that contributes to global warming. Achieving optimal yields while improving nitrogen use efficiency requires a balanced, real-time nitrogen application approach. This strategy allows for precise nitrogen delivery based on the crop's specific growth needs, maximizing yield potential, enhancing environmental sustainability, and ensuring that nitrogen resources are used effectively throughout the growing season. According to Patra et al. (2022), mid-November to the first week of December is the ideal time for maize sowing.

Optimizing crop geometry and nitrogen management is fundamental to enhancing the economic returns and productivity of quality protein maize (QPM) and conventional maize. These agronomic practices influence yield, input costs, nutrient use efficiency, and overall profitability, while also supporting environmental sustainability. This paper discusses the roles of optimal plant density and nitrogen application in maximizing protein quality of QPM and economic viability. Through an integrated approach, these practices enhance resource efficiency, improve grain quality, and reduce the risk of crop lodging, ultimately supporting sustainable agricultural systems.

To facilitate the broader dissemination and adoption of Quality Protein Maize (QPM) hybrids, it is essential to gain a deeper understanding of how QPM performs under different agronomic management practices. Among these practices, split nitrogen application and optimal plant population density are particularly important. By focusing on the cultivation of maize in West Bengal, India, this study aims to rigorously examine the effects of varying plant population densities and nitrogen management approaches on the nutrient partitioning and overall performance of QPM. The investigation seeks to determine how different levels of nitrogen, applied in a phased or split manner, and carefully managed plant spacing impact key growth metrics, nutrient uptake, and the protein quality of QPM. This research aims to provide practical insights for local farmers, enhancing QPM cultivation strategies that maximize yield and nutrient efficiency while addressing region-specific challenges.

II. MATERIALS AND METHODS

The experiment was conducted using a Split Plot Design (SPD) with three main plot treatments and five sub-plot treatments, replicated three times. The main plot treatments consisted of three different plant geometries: PG1 (60 x 30 cm) with a density of 55,555 plants ha⁻¹, PG2 (50 x 25 cm) with 80,000 plants ha⁻¹, and PG3 (40 x 20 cm) with 125,000 plants ha⁻¹. For sub-plot treatments, five nitrogen management strategies were tested: SN1 - conventional nitrogen management approach; SN2 - 25% nitrogen applied at basal, 25% at V8, 25% at VT, and 25% at R1; SN3 - 20% nitrogen applied at basal, 20% at V8, 40% at VT,

and 20% at R1; SN4 - 20% nitrogen at basal, 20% at V8, 30% at VT, and 30% at R1; and SN5 - 10% nitrogen at basal, 20% at V8, 40% at VT, and 30% at R1. In this experimental area, the conventional nitrogen management commonly practiced by farmers involves applying 50% of nitrogen at basal, followed by 25% at the knee height stage and 25% at VT.

For sowing, carefully selected seeds of the VL QPM hybrid 59 were used, chosen for their health, full maturity, and robust size. This hybrid variety has a growth period of about 140 to 155 days and is noted for its resistance to two major diseases: Turcicum Leaf Blight (TLB) and Maydis Leaf Blight (MLB), which are common threats in maize production. Additionally, VL QPM hybrid 59 is recognized for its high yield potential, typically producing between 6.5 to 7.5 t ha⁻¹ under optimal growing conditions. This variety not only ensures resilience against key diseases but also supports the objective of achieving substantial yield outputs in the experiment.

All data gathered throughout the study were statistically analyzed through analysis of variance (ANOVA) tailored for a split-plot design. This analysis was conducted using R software (version 4.3.3), allowing for precise calculation of critical differences and standard error of the mean to evaluate treatment effects. Additionally, a pooled analysis across two years was performed, adhering to the statistical methodology outlined by Gomez and Gomez (1983) to ensure robustness of results over time. The findings are reported at a 5% significance level (P=0.05), providing a reliable basis for interpreting treatment differences.

III. RESULTS AND DISCUSSION

3.1 Grain Yield (t ha⁻¹):

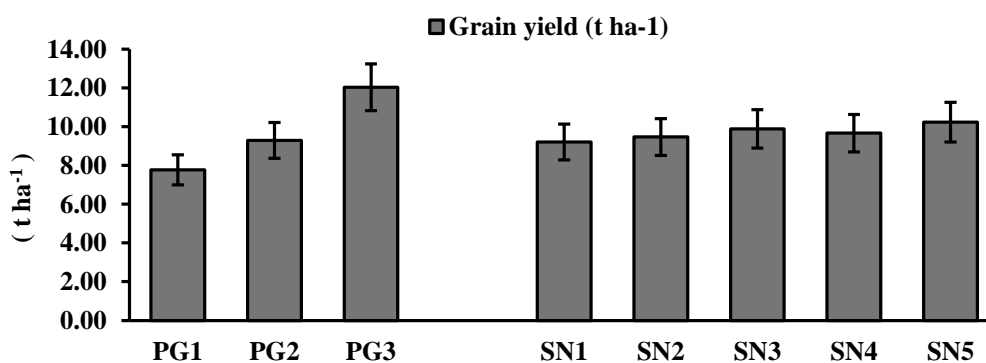


FIGURE 1: Graphical representation of grain yield (t ha⁻¹) of QPM as influenced by plant geometry and split nitrogen management.

Among crop geometry, significantly higher grain yield was observed in PG3 (12.03 t ha⁻¹) followed by PG2 (9.29 t ha⁻¹) and statistically lower grain yield was found in PG1 (7.77 t ha⁻¹) (pooled data of both years).

Among varying nitrogen management, grain yield varied significantly during both years of study. Significantly higher grain yield was observed in SN5 (10.23 t ha⁻¹) followed by SN3 (9.89 t ha⁻¹) and statistically lower grain yield was recorded in SN1 (9.21 t ha⁻¹) (pooled data of both years).

At lower planting densities, each maize plant can fully utilize the available resources, which generally leads to improved individual plant growth and better production attributes. When plant density is low, as in the case of 55,555 plants ha⁻¹ (PG1), plants experience minimal competition for essential resources such as light, water, and nutrients. This favorable environment allows each plant to grow more robustly and produce larger, well-developed cobs. However, the reduced overall plant population also leads to a lower total cob count per hectare due to fewer plants. Increasing plant density from 55,555 to 125,000 plants ha⁻¹ (PG3) results in a higher total number of cobs per unit area, as more plants contribute to cob production (IIMR, 2015a; IIMR, 2015e). However, this increase in plant population intensifies inter-plant competition for resources. Due to this competition, each individual plant produces smaller cobs, which can reduce per-plant yield. The increased competition particularly impacts the availability of resources such as nitrogen and water, crucial for cob development, thus leading to a decrease in the average cob size. At higher densities, mutual shading and crowding among plants increase, which negatively affects the growth of individual plants (Dar et al., 2014). This higher density fosters competition not only among neighboring plants but also between the vegetative (stalk and leaves) and reproductive (cob) parts within each plant, as both require substantial resources for development. Such competition can limit the availability of nutrients and energy for grain filling, potentially affecting the quality and weight of the cobs (Dutta et al., 2015). Interestingly, the PG3 treatment (40 x 20 cm

spacing, 125,000 plants ha⁻¹) achieves the highest grain yield (t ha⁻¹) compared to the lower density configurations (PG1 and PG2). This outcome can likely be attributed to the higher total number of plants contributing to cob production per unit area.

The SN5 nitrogen management strategy, which involves applying nitrogen in a split pattern of 10% at basal, 20% at the V8 stage (eight-leaf stage), 40% at the VT stage (tasseling), and 30% at the R1 stage (silking), significantly enhances grain yield (Ahmed and Patra, 2025). This specific nitrogen application schedule ensures a higher availability of nitrogen during the crop's critical reproductive stages, particularly the grain-filling phase. By supplying a substantial portion of nitrogen later in the growth cycle, especially at VT and R1 stages, SN5 supports optimal nutrient availability precisely when the plants have the highest demand for nitrogen to support reproductive growth (Chaudhary et al., 2015). This targeted late-season nitrogen side-dressing promotes increased nitrogen uptake by the plants, leading to improved assimilation of not only nitrogen but also other essential soil nutrients. This comprehensive nutrient absorption boosts the physiological processes necessary for robust cob and grain development (DMR, 2008). As a result, SN5 contributes significantly to yield-enhancing traits, ultimately increasing overall grain yield (t ha⁻¹) when compared to other nitrogen management strategies (DMR, 2007a).

In comparison, the SN3 approach (20% nitrogen at basal, 20% at V8, 40% at VT, and 20% at R1) provides a moderate level of nitrogen during the reproductive stages but falls short of the late nitrogen concentration seen in SN5. Consequently, SN3 does not achieve the same level of nitrogen availability at the grain-filling stage, which can limit potential yield benefits. Meanwhile, the SN1 approach (50% nitrogen at basal, 25% at knee height stage, and 25% at VT) applies a large initial dose and smaller doses later, resulting in lower nitrogen availability during the crucial reproductive stages. This leads to comparatively lower nutrient uptake and reduced yield attributes (Ramu and Reddy, 2007).

3.2 Cost of Cultivation (Rs. ha⁻¹)

Cost of cultivation differed significantly as influenced by varying crop geometry during both years of the study. Among different crop geometry, statistically higher cost of cultivation was observed in PG3 (78,081.49 and 80,865.09 Rs. ha⁻¹) followed by PG2 (75,081.49 and 77,565.09 Rs. ha⁻¹) and significantly lowest cost of cultivation was recorded in PG1 (73,681.49 and 76,165.09 Rs. ha⁻¹) respectively during both years of experimentation.

Among varying nitrogen management practices, lowest cost of cultivation was recorded in SN1 (72,886.82 and 75,314.42 Rs. ha⁻¹) and the same cost of cultivation was recorded in the rest of the four nitrogen management treatments (76,296.82 and 78,794.42 Rs. ha⁻¹) respectively during both years of experimentation. The higher cost for SN2 through SN5 reflects the additional labor and management required for multiple split applications compared to the conventional single split approach of SN1.

The PG3 crop geometry (40 x 20 cm, 125,000 plants ha⁻¹) resulted in the highest cost of cultivation in both years. This was expected, as denser planting requires a larger number of seeds and increased labor for sowing, maintenance, and other field operations. Research has shown that higher plant densities often increase input requirements, particularly for labor and seed costs (Amanullah et al., 2017). This aligns with the current results, where higher costs in PG3 reflect its intensified input needs.

The cost of cultivation was lowest in SN1, where nitrogen was applied 50% as basal and 25% each at knee height and VT stages. By applying a large proportion of nitrogen early in the season, SN1 reduced labor and operational costs associated with subsequent applications. However, research indicates that such concentrated applications may lead to nitrogen losses through volatilization or leaching, thereby lowering nitrogen use efficiency (NUE) and potentially affecting yield (Fageria and Baligar, 2018).

3.3 Gross Return (Rs. ha⁻¹)

Gross return differed significantly as influenced by varying crop geometry during both years of the study. Among different crop geometry, statistically higher gross return was observed in PG3 (226,267.9 and 221,563.1 Rs. ha⁻¹) followed by PG2 (174,315.2 and 171,556.5 Rs. ha⁻¹) and significantly lowest values were recorded in PG1 (145,736.7 and 143,451.8 Rs. ha⁻¹) respectively during both years of experimentation. Pooled data of two years shows a similar trend.

Among varying nitrogen management practices, highest gross return was recorded in SN5 (193,258.8 and 187,730.6 Rs. ha⁻¹), followed by SN3 (185,929.8 and 182,480.2 Rs. ha⁻¹), and significantly lowest values were observed in SN1 (173,216.5 and 169,693.3 Rs. ha⁻¹) respectively during both years of experimentation as well as pooled data showed a similar trend.

The enhanced gross returns in PG3 can be attributed to the increased plant population, which typically results in a higher total biomass and grain yield per hectare. According to studies on optimal plant population density, increasing plant density up to a

certain threshold maximizes yield by improving light interception and nutrient use efficiency (Mason and Fischer, 2019). However, if density is too high, competition for resources may reduce individual plant yield, though this level was not reached in this experiment.

The split nitrogen application in SN5 aligns closely with the nutrient demand of the crop at key growth stages, enhancing nitrogen uptake and photosynthesis during critical phases (Thapa et al., 2019). Delaying a portion of nitrogen until the VT and R1 stages coincides with peak demand, which can improve grain filling and grain yield and ultimately results in higher gross return.

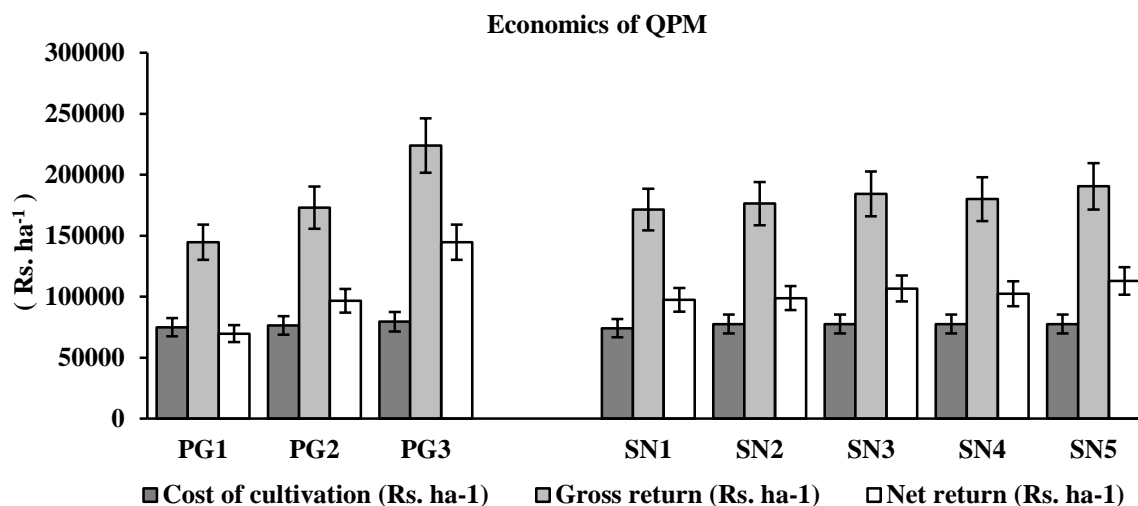


FIGURE 2: Graphical representation of Economics (Rs. ha⁻¹) of QPM as influenced by plant geometry and split nitrogen management.

3.4 Net Return (Rs. ha⁻¹)

Net return differed significantly as influenced by varying crop geometry during both years of the study. Among different crop geometry, statistically higher net return was observed in PG3 (148,186.38 and 140,998.04 Rs. ha⁻¹) followed by PG2 (99,233.74 and 93,991.41 Rs. ha⁻¹) and significantly lowest values were recorded in PG1 (72,055.18 and 67,286.66 Rs. ha⁻¹) respectively during both years of experimentation. Pooled data of two years shows a similar trend.

Among varying nitrogen management practices, highest net return was recorded in SN5 (116,961.9 and 108,936.20 Rs. ha⁻¹), followed by SN3 (109,633.0 and 103,685.79 Rs. ha⁻¹), and significantly lowest values were observed in SN1 (100,329.6 and 94,378.91 Rs. ha⁻¹) respectively during both years of experimentation as well as pooled data showed a similar trend.

PG3 recorded the highest net returns, due to the combination of high gross returns and efficient utilization of resources. These findings align with evidence that denser plantings, when combined with adequate nutrient and water management, can achieve higher yields and returns (Islam et al., 2020). PG1, having the lowest density, resulted in smallest net returns, as the limited plant population constrained biomass production and total economic yield.

SN5 achieved the highest net returns. This split application approach allows plants to utilize nitrogen efficiently over time, reducing potential nitrogen losses and leading to greater profitability. Studies have confirmed that delayed applications can minimize nitrogen wastage and increase yield, thus positively impacting net returns (Prasad and Power, 2020).

3.5 Benefit-Cost (B:C) Ratio

B:C ratio differed significantly as influenced by varying crop geometry during both years of the study. Among different crop geometry, statistically higher B:C ratio was observed in PG3 (2.90 and 2.75) followed by PG2 (2.32 and 2.21) and significantly lowest values were recorded in PG1 (1.98 and 1.88) respectively during both years of experimentation. Pooled data of two years shows a similar trend.

Among varying nitrogen management practices, highest B:C ratio was recorded in SN5 (2.54 and 2.37), followed by SN4 (2.43 and 2.31), and significantly lowest values were observed in SN1 (2.31 and 2.22) respectively during both years of experimentation as well as pooled data showed a similar trend.

PG3 recorded the highest B:C ratio, suggesting that, despite higher input costs, the returns on investment were maximized at higher plant densities. The high B:C ratio for PG3 is consistent with findings that optimized plant densities improve economic efficiency by maximizing yield potential and return on resources invested (Kumar and Patel, 2021). The lower B:C ratios in PG1 confirm that suboptimal densities reduce financial returns.

SN5 had the highest B:C ratio, followed by SN3, which also used a staggered approach (20% basal, 20% at V8, 40% at VT, 20% at R1). The higher B:C ratios in SN5 and SN3 indicate that staggered applications not only increase yield but also enhance economic efficiency. Efficient nitrogen timing optimizes the crop's ability to absorb and use nitrogen effectively, as confirmed by studies linking strategic nitrogen applications to improved economic outcomes (Choudhary and Gupta, 2019).

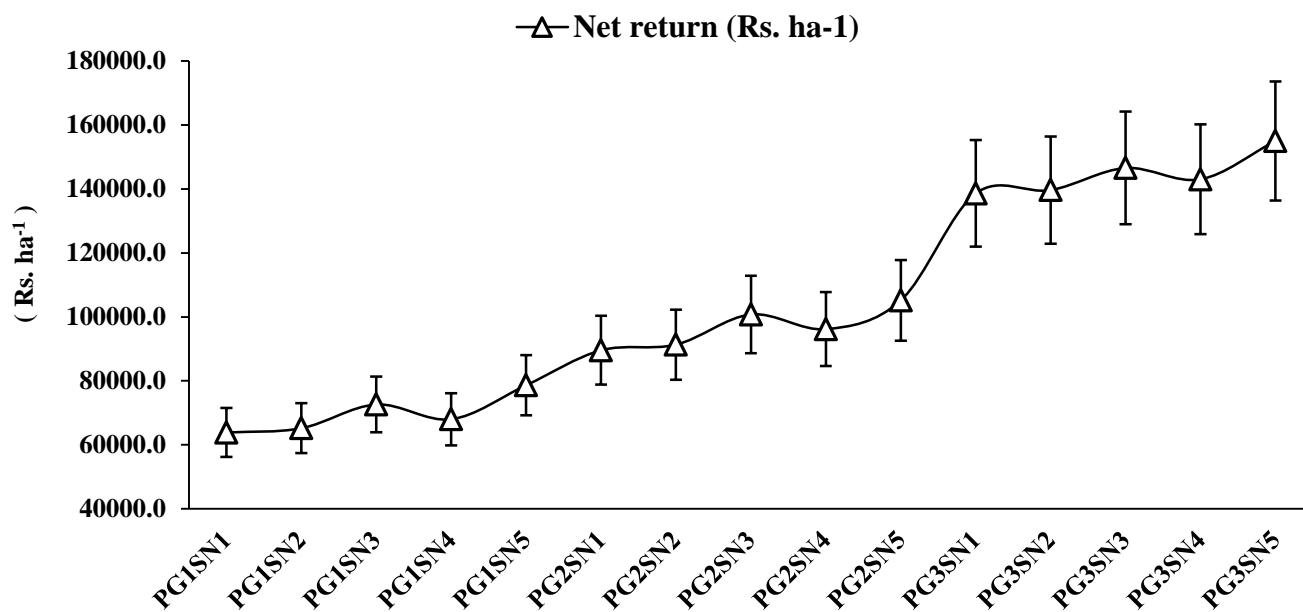


FIGURE 3: Treatment combinations of plant geometry and split nitrogen management on net return (t ha⁻¹) of QPM.

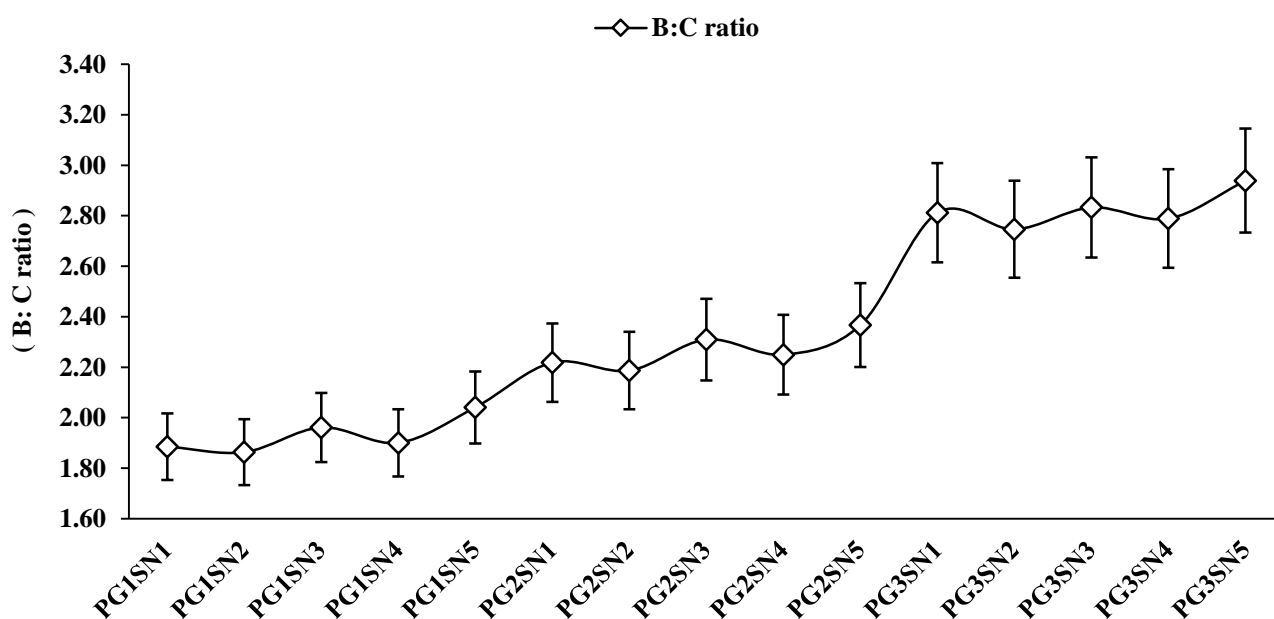


FIGURE 4: Treatment combinations of plant geometry and split nitrogen management on B:C ratio of QPM.

TABLE 1
IMPACT OF PLANT GEOMETRY AND SPLIT NITROGEN MANAGEMENT ON THE ECONOMICS OF QPM

Treatments	Cost of cultivation (Rs. ha ⁻¹)		Gross return (Rs. ha ⁻¹)		Net return (Rs. ha ⁻¹)		B:C ratio	
	2021	2022	2021	2022	2021	2022	2021	2022
Plant geometry								
PG1	73,681.49	76,165.09	1,45,736.70	1,43,451.80	72,055.18	67,286.66	1.98	1.88
PG2	75,081.49	77,565.09	1,74,315.20	1,71,556.50	99,233.74	93,991.41	2.32	2.21
PG3	78,081.49	80,865.09	2,26,267.90	2,21,563.10	1,48,186.38	1,40,998.04	2.9	2.75
Split Nitrogen Management								
SN1	72,886.82	75,314.42	1,73,216.50	1,69,693.30	1,00,329.60	94,378.91	2.37	2.25
SN2	76,296.82	78,794.42	1,77,079.70	1,75,499.60	1,00,782.90	96,705.16	2.31	2.22
SN3	76,296.82	78,794.42	1,85,929.80	1,82,480.20	1,09,633.00	1,03,685.79	2.43	2.31
SN4	76,296.82	78,794.42	1,81,048.20	1,78,881.90	1,04,751.30	1,00,087.45	2.36	2.26
SN5	76,296.82	78,794.42	1,93,258.80	1,87,730.60	1,16,961.90	1,08,936.20	2.54	2.37

Treatment details:

- **Main-plot:** PG1 - 60 x 30 cm (55,555 plants ha⁻¹), PG2 - 50 x 25 cm (80,000 plants ha⁻¹), PG3 - 40 x 20 cm (125,000 plants ha⁻¹)
- **Sub-plot:** SN1 - (50% as basal + 25% at knee height stage + 25% VT), SN2 - (25% at basal + 25% at V8 + 25% at VT + 25% at R1), SN3 - (20% at basal + 20% at V8 + 40% at VT + 20% at R1), SN4 - (20% at basal + 20% at V8 + 30% at VT + 30% at R1), SN5 - (10% at basal + 20% at V8 + 40% at VT + 30% at R1)

IV. CONCLUSION

The results clearly indicate that implementing a high-density planting configuration (PG3) alongside a well-timed, staggered nitrogen management strategy (SN5) delivers the most substantial economic benefits. This approach optimizes nitrogen use efficiency by ensuring the nutrient is available during critical growth phases, thereby supporting robust vegetative growth and effective grain filling. As a result, both biomass and grain production are significantly enhanced, leading to superior gross and net returns compared to other treatment combinations. Therefore, the integration of the PG3 crop geometry and SN5 nitrogen management can serve as a highly effective agronomic strategy, offering considerable potential for maximizing profitability in comparable maize-based cropping systems.

CONFLICT OF INTEREST

The authors declared no conflict of interest

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Valorization of Pomegranate Peel Waste: Extraction of Phenolic-Rich Fractions and Their Antioxidant Performance

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Abstract— Pomegranate (*Punica granatum L.*) peel, a byproduct of juice extraction, is rich in phenolics, flavonoids, and tannins. This study aimed to optimize the extraction of these bioactive compounds from pomegranate peel extract (PPE). It also evaluated PPE's efficacy in inhibiting lipid peroxidation in a high-unsaturated-lipid system. Total phenolic content (TPC) and DPPH scavenging activity (DPPH•-SA) were used as indicators of antioxidant potential. Extraction was optimized using Response Surface Methodology (RSM) with a Box–Behnken Design (BBD) to assess the effects of temperature, time, and ethanol concentration. The optimal conditions were set at 65°C for 60 min using 70% ethanol, yielding a TPC = 231.8 mg GAE/g dry weight. The DPPH•-SA of PPE was 91.8%, with an IC_{50} = 16.92 µg/mL. The antioxidant performance of PPE was validated in refined, bleached, deionized sunflower oil (SFO) using the Rancimat assay. PPE at 250 µg/g extended the SFO induction period from 8.32 to 15.90 h. This resulted in a Relative Stability Index = 1.91 and a Free Radical Scavenging = 91.11%. These findings demonstrate that PPE's antioxidant activity is comparable to synthetic antioxidants like TBHQ and BHT. This makes it a sustainable alternative to synthetic antioxidants and a valuable option for food and healthcare applications.

Keywords— Pomegranate peel extract, Agro-industrial waste, Valorization, Polyphenols, Response Surface Methodology (RSM), Sustainable food preservation.

I. INTRODUCTION

Pomegranate (*Punica granatum L.*) is widely cultivated in the Middle East, Africa, and Asia and is valued for its nutritional and functional properties (Filipovic et al., 2025; Mohlamonyane et al., 2024). During industrial processing, a substantial portion of the fruit, primarily the peel, is discarded as waste, accounting for up to 40% of the total fruit mass (Himel et al., 2024). This byproduct represents a significant and underutilized source of bioactive compounds.

Pomegranate peel is particularly rich in polyphenolic constituents, including ellagitannins (e.g., punicalagins), phenolic acids, and flavonoids (Liu et al., 2024; Vasisht et al., 2024). These compounds are recognized for their strong antioxidant properties, largely due to their ability to donate hydrogen atoms or electrons to reactive species (Andrade et al., 2024; Salim et al., 2023). As a result, pomegranate peel extract (PPE) has attracted increasing attention as a natural antioxidant that

inhibits lipid oxidation in food systems. The replacement of synthetic antioxidants with plant-derived alternatives has become a key objective in food preservation, driven by consumer demand for safer and more sustainable ingredients (Salim et al., 2023).

The recovery of phenolic compounds from plant matrices depends strongly on extraction conditions. Parameters such as solvent composition, temperature, and extraction time influence both extraction efficiency and the integrity of bioactive molecules (Liu et al., 2024; Rashed et al., 2018). Aqueous ethanol is commonly employed due to its suitable polarity for solubilizing a broad range of phenolic compounds (Nawaz et al., 2020). However, conventional extraction methods often suffer from limited mass transfer and prolonged processing times, thereby reducing overall efficiency.

To address these limitations, intensified extraction techniques have been developed. Among them, ultrasonic–microwave-assisted extraction (UMAE) combines the effects of acoustic cavitation and rapid internal heating, leading to enhanced disruption of plant cell structures and improved solvent penetration (Kaderides et al., 2021; Rashed et al., 2016). This dual mechanism accelerates the release of intracellular compounds and has been shown to improve the recovery of phenolic compounds compared with conventional approaches.

Despite the recognized potential of pomegranate peel as a source of natural antioxidants, the relationship between extraction conditions, phenolic recovery, and functional performance in lipid systems remains insufficiently clarified. In particular, linking extraction efficiency with practical antioxidant performance under oxidative conditions is essential for evaluating real-world applicability.

In this context, the present study investigates the extraction of phenolic-rich fractions from pomegranate peel using an intensified extraction approach. The antioxidant capacity of the obtained extract was evaluated using radical-scavenging assays and further validated in a lipid system through thermo-oxidative stability analysis. This work aims to demonstrate the potential of pomegranate peel as a sustainable source of natural antioxidants for food preservation applications.

II. MATERIALS AND METHODS

2.1 Sample Collection and Reagents:

Pomegranate (*Punica granatum* L.) fruits were collected from Suzhou, Anhui, China, in September 2024. The peels were manually separated, rinsed with tap water, and dried in a hot-air oven at $40 \pm 2^\circ\text{C}$ for 24 h. The dried material was ground and passed through a 60-mesh sieve to obtain a fine powder. Moisture content, determined at 105°C , was 8.4% (w/w). The powder was stored in sealed containers at room temperature and protected from light.

All chemicals and solvents were of analytical grade and obtained from commercial suppliers, including Sinopharm Chemical Reagent Co. (China), Macklin (Shanghai, China), TCI Europe N.V. (Belgium), and Sigma-Aldrich (USA).

2.2 Extraction Processes:

Polyphenols were extracted from PP using ultrasonic/microwave-assisted extraction (UMAE) and maceration-assisted extraction (MAC). UMAE was optimized by Response Surface Methodology (RSM) with a Box–Behnken design (BBD) to maximize recovery, while maceration extraction (MAC) served as a control. This comparison highlights UMAE advantages, including higher efficiency, reduced time and energy use, with temperature, time, and solvent concentration as key parameters.

2.3 Maceration Extraction:

Maceration extraction (MAC) was used as the conventional control (Zhang et al., 2024) with slight modifications. Ten grams of PP powder were mixed with 400 mL of 70:30 (v/v) ethanol–water and incubated at 60°C for 60 min in a thermostatic shaking water bath.

2.4 Ultrasonic/Microwave-Assisted Extraction:

UMAE was employed to enhance polyphenol recovery from PP, using combined ultrasonic and microwave energy (Rashed et al., 2016). Extraction was performed in a dual-mode reactor (200 W ultrasound, 150 W microwave), in which 10 g of PP was mixed with 300 mL of 70% ethanol–water at a 1:30 (w/v) ratio (Vargas-Torrico et al., 2024) and treated at $60 \pm 1^\circ\text{C}$ for 10 min. The extract was filtered, concentrated, diluted to 50 mL with distilled water, and stored at 4°C . The extract was vacuum-filtered, concentrated by rotary evaporation at 50°C , reconstituted to 50 mL with distilled water, and stored at -4°C for analysis.

2.5 Colorimetric Estimation of Polyphenols:

Total phenolic content (TPC) was determined using the Folin-Ciocalteu method according to Liu et al. (2024), with gallic acid (0–200 mg/L) for calibration. Results were expressed as mg gallic acid equivalents per gram of dry matter (mg GAE/g DM). All measurements were performed in triplicate and reported as mean \pm standard deviation.

2.6 DPPH Radical Scavenging Assay:

Antioxidant capacity was evaluated using the DPPH radical scavenging assay (DPPH•-SA) following Rashed et al. (2022), where PPE (10–160 μ g/mL) was mixed with 60 μ M DPPH, incubated for 30 min in the dark, and measured at 517 nm; TBHQ and BHT were used as positive controls. IC₅₀ values were obtained from inhibition versus log concentration plots, and all experiments were conducted in triplicate.

$$\text{DPPH} \bullet -\text{SA}\% = \frac{A_0 - A_1}{A_0} \times 100 \quad (1)$$

Where A_0 is the absorbance of the control (DPPH solution without sample), and A_1 is the absorbance of the sample (with PPE).

2.7 Experimental Design and Optimization:

Optimization was performed using RSM combined with Box–Behnken Design (BBD). Extraction parameters, including temperature (50–80°C), time (40–80 min), and ethanol concentration (60–80%), were optimized to maximize the yields of TPC and DPPH•-SA. Experimental design and statistical analysis were carried out using Design-Expert 13.0 (Stat-Ease Inc., USA). Experimental data were fitted to second-order polynomial (quadratic) models describing the relationship between extraction parameters and measured responses. The general form of the response surface model is expressed as Eq. (2):

$$Y = \beta_0 + \sum_{i=1}^3 \beta_i X_i + \sum_{i=1}^3 \beta_{ii} X_i^2 + \sum_{i=1}^3 \sum_{j=1}^3 \beta_{ij} X_i X_j \quad (2)$$

where: Y is the response (TPC or DPPH•-SA), β_0 is the intercept, β_i , β_{ii} , and β_{ij} represent linear, quadratic, and interaction effects, respectively. X_i and X_j are the coded independent variables.

Model adequacy was assessed using analysis of variance (ANOVA) to test the significance of regression coefficients ($p < 0.05$). Goodness-of-fit was evaluated through R^2 , adjusted R^2 , predicted R^2 , and adequate precision. Finally, the RSM-predicted optimal extraction conditions were experimentally validated. The observed TPC and DPPH•-SA values under optimal conditions were compared with the predicted values. Experimental validation is crucial, as strong agreement between actual and predicted values confirms the model's accuracy and practical relevance.

2.8 Statistical Analysis:

All results are expressed as mean \pm standard deviation ($n = 3$). A one-way ANOVA followed by Tukey's test revealed significant differences at $p < 0.05$. Statistical analyses were conducted using SPSS 25.0 (IBM, USA).

III. RESULTS AND DISCUSSION

3.1 Effect of the Extraction Process on the Yield:

The extraction yield of crude extract differed noticeably between the applied methods. Maceration resulted in a relatively lower yield of 12.8% (w/w), reflecting limited recovery under conventional diffusion-controlled conditions. The prolonged solvent contact enables gradual extraction; however, mass transfer remains limited, reducing overall efficiency. In contrast, ultrasonic–microwave-assisted extraction (UMAE) produced a higher extract yield of 18.5% (w/w). This increase can be attributed to enhanced mass transfer driven by the combined action of ultrasonic and microwave energy. Ultrasonic cavitation facilitates the release of intracellular constituents, while microwave irradiation accelerates solvent penetration through rapid internal heating. The combined effects improve solvent accessibility to the plant matrix and promote more efficient transfer of solutes into the extraction medium. As a result, UMAE provides a higher recovery of crude extract in a shorter processing time than maceration. These numbers are consistent with other studies on PP extraction (Rashed et al., 2016; Vargas-Torrico et al., 2024).

3.2 Total Phenolic Content:

SEM results support the TPC findings, with UMAE causing more severe cell wall disruption than maceration, enhancing solvent penetration and phenolic diffusion. UMAE produced a significantly higher TPC = 225.6 mg GAE/g DW ($p < 0.05$), compared to 196.5 mg GAE/g DW for maceration (Fig. 1a). This confirms UMAE's superior extraction efficiency. Similar results were found by Sweidan et al. (2023), with a maximum TPC = 297.70 ± 1.73 mg GAE/g DW in ethanol-based extracts. The differences in results can be attributed to variations in solvent concentration, particle size, and extraction energy input. Ethanol's polarity enhances solute-solvent interactions, improving phenolic extraction efficiency (Marchi et al., 2015; Rashed et al., 2016).

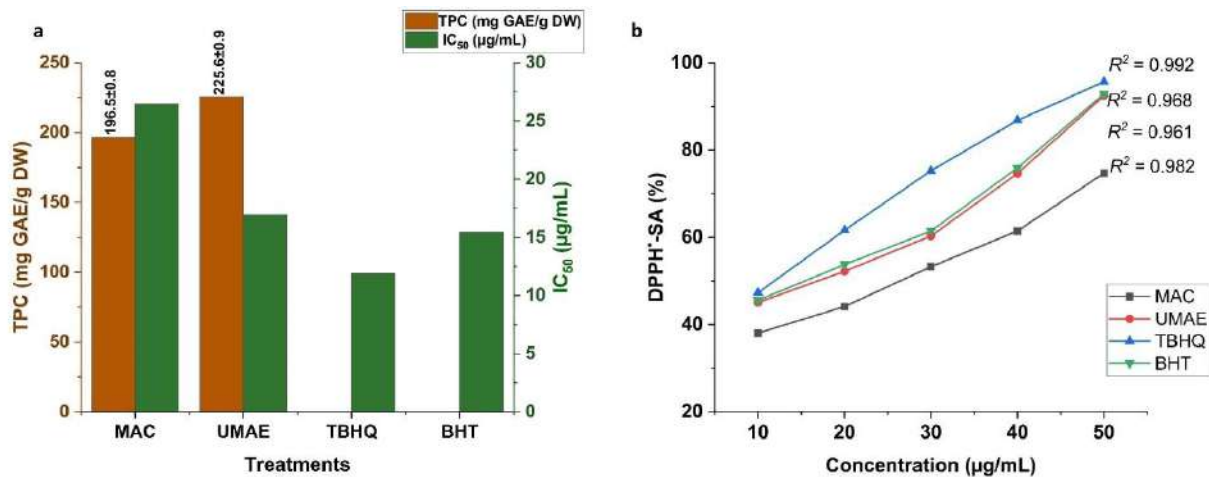


FIGURE 1. (a) Total phenolic content (TPC) and DPPH scavenging (DPPH•-SA) in terms of IC₅₀ (µg/mL), and (b) DPPH•-SA (%) of maceration extraction (MAC), ultrasonic/microwave-assisted extraction (UMAE), TBHQ, and BHT.

3.3 DPPH• Scavenging:

UMAE demonstrated the highest antioxidant activity, with an IC₅₀ of 16.92 µg/mL (Fig. 1b). At 50 µg/mL, UMAE achieved 92.46% inhibition, outperforming maceration (IC₅₀ of 26.45 µg/mL; 74.70% inhibition). UMAE and BHT showed similar IC₅₀ values ($p > 0.05$), indicating comparable radical-scavenging potency. BHT had an IC₅₀ = 15.43 µg/mL and 92.86% inhibition. TBHQ showed the highest activity (IC₅₀ = 11.89 µg/mL, 96.66% inhibition), significantly outperforming all other treatments ($p < 0.05$). These results align with previous studies indicating TBHQ's superior antioxidant activity (Bi et al., 2025; Shanlee et al., 2025). The concentration-dependent increase in DPPH• inhibition (10–50 µg/mL) confirms a dose-response relationship (Pfleger et al., 2025; Sweidan et al., 2023). The strong antioxidant activity of UMAE suggests PPE as a viable natural alternative to BHT. This is crucial in stabilizing high-fat food products. Phenolics in PPE are key contributors to antioxidant activity, neutralizing free radicals and reducing oxidative stress (More & Arya, 2024). TPC is a reliable indicator of antioxidant activity, with higher values often linked to stronger antioxidant activity (Khan et al., 2025). DPPH• results further confirm polyphenols' role in neutralizing free radicals and chelating transition metals (Yu et al., 2025).

3.4 Optimization Results:

RSM combined with BBD was used to optimize extraction parameters. This approach evaluates multiple factors simultaneously, providing more efficient optimization than single-variable methods (Giri et al., 2023). Significant interactions among extraction temperature, time, and ethanol concentration were identified, optimizing both TPC and DPPH•-SA.

3.5 Statistical Interpretation and Model Predictions:

RSM showed that extraction temperature had the greatest effect on TPC and DPPH•-SA, followed by time and ethanol concentration. Diagnostic analyses, including residual behavior and predictive reliability, are provided in Fig. 2. These results confirm RSM's efficiency for multi-factor optimization, as shown by previous studies (Giri et al., 2023; Kim & Yoon, 2023). The regression equations for TPC and DPPH•-SA are provided below:

$$Y_1 = 230.36 - 11.86A - 1.02B - 0.1625C - 2.08AB + 0.5500AC + 0.8250BC - 18.56A^2 - 3.23B^2 - 9.45C^2 \quad (3)$$

$$Y_2 = 91.60 - 2.80A - 0.0500B + 0.1500C - 0.0250AB + 0.2750AC + 0.6250BC - 5.69A^2 - 1.19B^2 - 3.64C^2 \quad (4)$$

where: Y_1 and Y_2 refer to the TPC (mg GAE/g DW) response and DPPH•-SA (%) response, respectively; A refers to extraction temperature (°C); B refers to extraction time (min); and C refers to ethanol concentration (%). These equations describe the relationship between factors and responses, confirming the model's excellent performance.

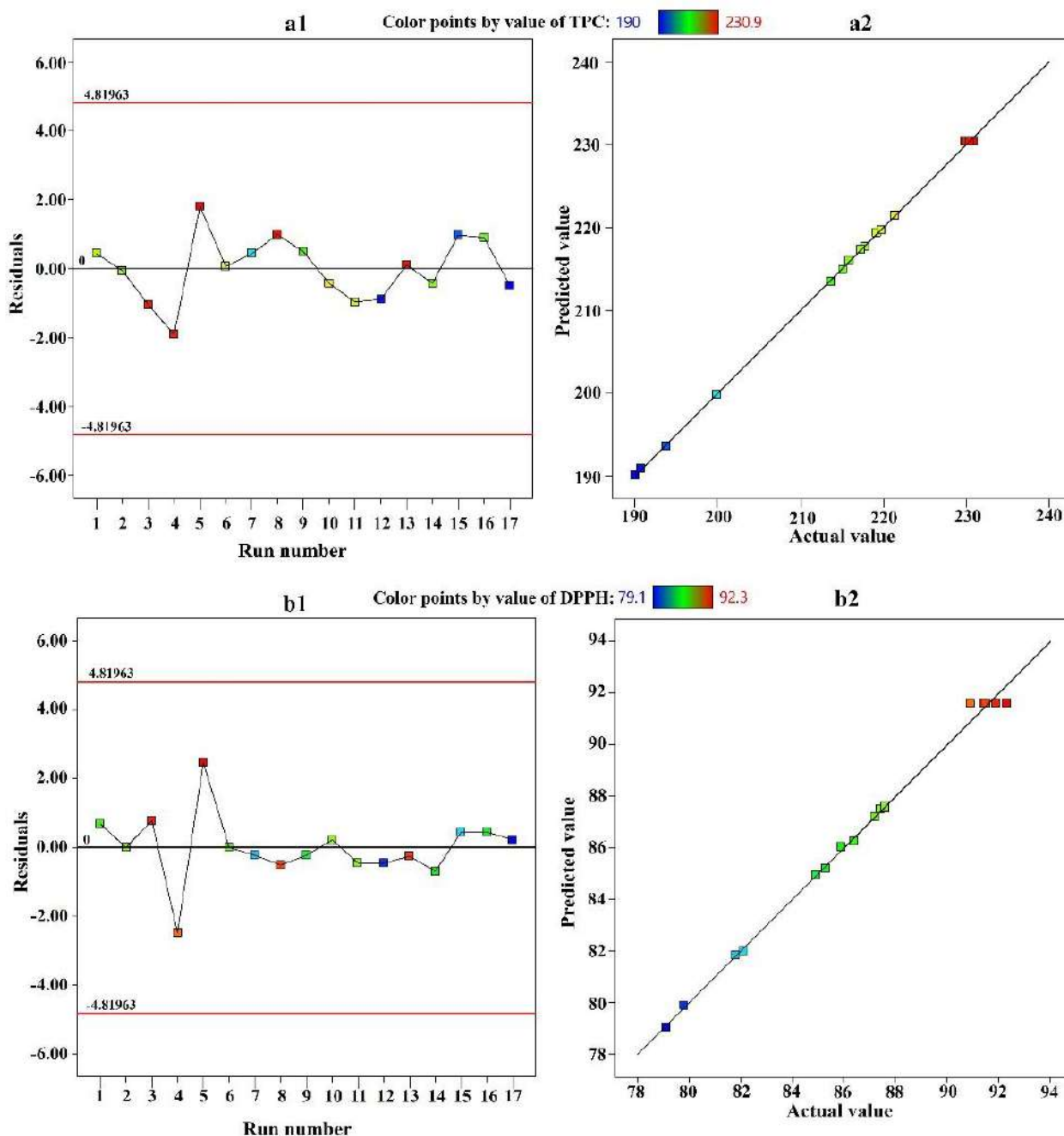


FIGURE 2: Diagnostic evaluation plots for RSM models based on BBD: correlations between residuals and runs (a1, b1), and between predicted and actual values (a2, b2) for TPC and DPPH•-SA%, respectively.

Table 1 presents the BBD matrix with the actual and coded levels of extraction parameters. Runs 3-5, 8, and 13 recorded the highest actual values for both TPC (229.8 – 230.9 mg GAE/g DW) and DPPH•-SA% (90.9 – 92.3%). Among these, Run 5 achieved the highest TPC (231.8 mg GAE/g DW) and DPPH•-SA (92.3%) under optimal conditions of 65°C for 60 min in 70% ethanol. The predicted and actual values are closely aligned, confirming the model's accuracy. The residual and average Absolute Percent Error (APE) for TPC were 0.5 and 0.22%, respectively. For DPPH•-SA, these values were -0.2 and 0.22%, demonstrating excellent model predictability and reliability. These small deviations (< 0.5%) validate the robustness and predictive capability of the quadratic models derived using RSM with BBD, ensuring minimal experimental deviation.

TABLE 1
BOX-BEHNKEN DESIGN (BBD) MATRIX WITH ACTUAL FACTOR LEVELS, ACTUAL AND PREDICTED RESPONSES, RESIDUALS, AND ABSOLUTE PERCENT ERRORS (APE%) FOR TPC (Y₁) AND DPPH•-SA (Y₂) OF POMEGRANATE PEEL EXTRACT (PPE)

Run	A: Temperature (°C)	B: Time (min)	C: Ethanol (%)	TPC Actual (mg GAE/g DW)	TPC Predicted (mg GAE/g DW)	Residual	APE%	DPPH•-SA Actual (%)	DPPH•-SA Predicted (%)	Residual	APE%
1	65	40	80	217.8	217.7	0.1	0.05	86.4	86.3	0.1	0.12
2	65	80	80	217.3	217.3	0	0	87.6	87.6	0	0
3	65	60	70	230	230.4	-0.4	0.17	91.9	91.6	0.7	0.76
4	65	60	70	229.8	230.4	-0.6	0.26	90.9	91.6	-0.7	0.77
5	65	60	70	230.9	230.4	0.5	0.22	92.3	91.6	-0.2	0.22
6	65	40	60	219.7	219.7	0	0	87.2	87.2	0	0
7	80	40	70	199.9	199.8	0.1	0.05	81.8	81.9	-0.1	0.12
8	65	60	70	230.7	230.4	0.3	0.13	91.4	91.6	0.2	0.22
9	50	60	80	213.6	213.5	0.1	0.05	84.9	85	-0.1	0.12
10	50	80	70	221.4	221.5	-0.1	0.05	87.6	87.6	0	0
11	50	40	70	219.2	219.4	-0.2	0.09	87.4	87.5	-0.1	0.11
12	80	60	80	190.7	190.9	-0.2	0.1	79.8	79.9	-0.1	0.13
13	65	60	70	230.4	230.4	0	0	91.5	91.6	-0.1	0.11
14	65	80	60	215.9	216	-0.1	0.05	85.9	86.1	-0.2	0.23
15	80	80	70	193.8	193.6	0.2	0.1	82.1	82	0.1	0.12
16	50	60	60	215.1	214.9	0.2	0.09	85.3	85.2	0.1	0.12
17	80	60	60	190	190.1	-0.1	0.05	79.1	79.1	0	0

*Center points: Runs 3-5, 8, and 13. Residual = Actual value – Predicted value; APE = |Residual/Actual value| × 100.
 Average APE: TPC = 0.10%; DPPH•-SA = 0.17%.*

3.6 Model Significance and Analysis of Variance:

ANOVA results for the quadratic models of TPC (Y₁) and DPPH•-SA (Y₂) are summarized in Tables 2 and 3. Both models were significant (p < 0.0001), with non-significant lack-of-fit values (p > 0.05) confirming the models' predictive reliability. For both models, lack-of-fit p-values were 0.8344 (TPC) and 0.9479 (DPPH•-SA). This confirms that the quadratic models represent the relationships between extraction parameters and responses. Significant terms (temperature, time, and ethanol level) accounted for the variance in both responses.

For TPC, the model showed an R² = 0.9997, adjusted R² = 0.9993, and predicted R² = 0.9987. These values indicate a near-perfect correlation between actual and predicted values, confirming the model's accuracy. Adeq Precision (136.55) and a low coefficient of variation (0.18%) demonstrate excellent model precision. Temperature (A) had the greatest linear effect (p < 0.0001), followed by the quadratic terms A², B², and C². These findings confirm strong curvature, indicating non-linear interactions in the design space.

For DPPH•-SA, the quadratic model achieved R² = 0.9957. The adjusted R² = 0.9901 and the predicted R² = 0.9883 indicate a reliable fit to the data. The model showed Adeq Precision (39.28) and coefficient of variation (0.48%). Extraction temperature (A) had the greatest influence (p < 0.0001), followed by significant quadratic terms (A², B², C²). The BC interaction was significant (p = 0.0199), indicating a synergistic effect between extraction time and ethanol concentration. These findings confirm that temperature is the primary factor influencing both TPC and DPPH•-SA, with extraction time and ethanol concentration also modulating their efficiency. High determination coefficients and strong precision indices validate the robustness of RSM models, with lack-of-fit confirming predictive accuracy.

TABLE 2
ANALYSIS OF VARIANCE (ANOVA) FOR THE QUADRATIC MODEL FOR POMEGRANATE PEEL EXTRACT'S
TOTAL PHENOLIC CONTENTS (mg GAE/g DW)

Source	Sum of Squares	df	Mean Square	F-value	p-value	Note
Model	3161.63	9	351.29	2377.04	< 0.0001	significant
A (Temperature)	1125.75	1	1125.75	7617.46	< 0.0001	
B (Time)	8.4	1	8.4	56.87	0.0001	
C (Ethanol)	0.2112	1	0.2112	1.43	0.2708	
AB	17.22	1	17.22	116.54	< 0.0001	
AC	1.21	1	1.21	8.19	0.0243	
BC	2.72	1	2.72	18.42	0.0036	
A ²	1449.63	1	1449.63	9809.03	< 0.0001	
B ²	43.93	1	43.93	297.24	< 0.0001	
C ²	376.41	1	376.41	2546.99	< 0.0001	
Residual	1.03	7	0.1478			
Lack of Fit	0.1825	3	0.0608	0.2856	0.8344	not significant
Pure Error	0.852	4	0.213			
Cor Total	3162.66	16				

Standard deviation = 0.3844; Mean = 215.66; C.V. % = 0.1783; R² = 0.9997; Adjusted R² = 0.9993; Predicted R² = 0.9987; Adeq Precision = 136.5469

TABLE 3
ANALYSIS OF VARIANCE (ANOVA) FOR THE QUADRATIC MODEL FOR THE DPPH•-SA (%) OF
POMEGRANATE PEEL EXTRACT

Source	Sum of Squares	df	Mean Square	F-value	p-value	Note
Model	278.75	9	30.97	178.44	< 0.0001	significant
A (Temperature)	62.72	1	62.72	361.35	< 0.0001	
B (Time)	0.02	1	0.02	0.1152	0.7442	
C (Ethanol)	0.18	1	0.18	1.04	0.3424	
AB	0.0025	1	0.0025	0.0144	0.9078	
AC	0.3025	1	0.3025	1.74	0.2283	
BC	1.56	1	1.56	9	0.0199	
A ²	136.2	1	136.2	784.7	< 0.0001	
B ²	5.94	1	5.94	34.21	0.0006	
C ²	55.71	1	55.71	320.97	< 0.0001	
Residual	1.21	7	0.1736			
Lack of Fit	0.095	3	0.0317	0.1131	0.9479	not significant
Pure Error	1.12	4	0.28			
Cor Total	279.96	16				

Standard deviation = 0.4166; Mean = 86.65; C.V. % = 0.4808; R² = 0.9957; Adjusted R² = 0.9901; Predicted R² = 0.9883; Adeq Precision = 39.2762

3.7 Response Surface Analysis:

Three-dimensional (Fig. 3a-c, Fig. 4a-c) and contour plots (Fig. 3d-f, Fig. 4d-f) revealed the optimal conditions for the highest TPC and DPPH•-SA. The highest TPC (230.9 mg GAE/g DW) and DPPH•-SA (92.3%) were obtained at 65°C for 60 min using 70% ethanol. The predicted maximum response for TPC was 230.4 mg GAE/g DW. For DPPH•-SA, it was 91.9%. Lower extraction conditions, e.g., 50°C, 40% ethanol, and 40 min, resulted in the lowest values. Intermediate conditions produced moderate TPC and DPPH•-SA values, indicating a balanced extraction. Ethanol concentration significantly influenced extraction efficiency, with 70% ethanol yielding the highest TPC and antioxidant activity.

The surface and contour plots of TPC (Fig. 3a-f) and DPPH•-SA (Fig. 4a-f) confirm optimal extraction conditions. They also demonstrate significant interactions among variables. Each plot clearly reflects the curvature of the response surface predicted by the quadratic model. Response surface plots indicate that extraction temperature and time were the primary factors influencing TPC and DPPH•-SA.

However, temperatures > 70°C resulted in a slight decrease in TPC, likely due to thermal degradation of phenolics. Ethanol (70%) yielded the highest TPC, suggesting it is the optimal solvent polarity for solubilizing both hydrophilic and lipophilic phenolics. DPPH•-SA increased with temperature and time up to approximately 65°C and 60 min, then it declined at higher temperatures and times. The optimal ethanol concentration, similar to TPC, was near 70%. Moderate ethanol levels improved antioxidant activity, whereas excessively high concentrations reduced extraction efficiency. The close alignment between the graphical trends and ANOVA outcomes demonstrates that the model reliably captured the experimental behavior. The response surfaces also provide valuable insights for optimizing the process and scaling up under controlled thermal conditions.

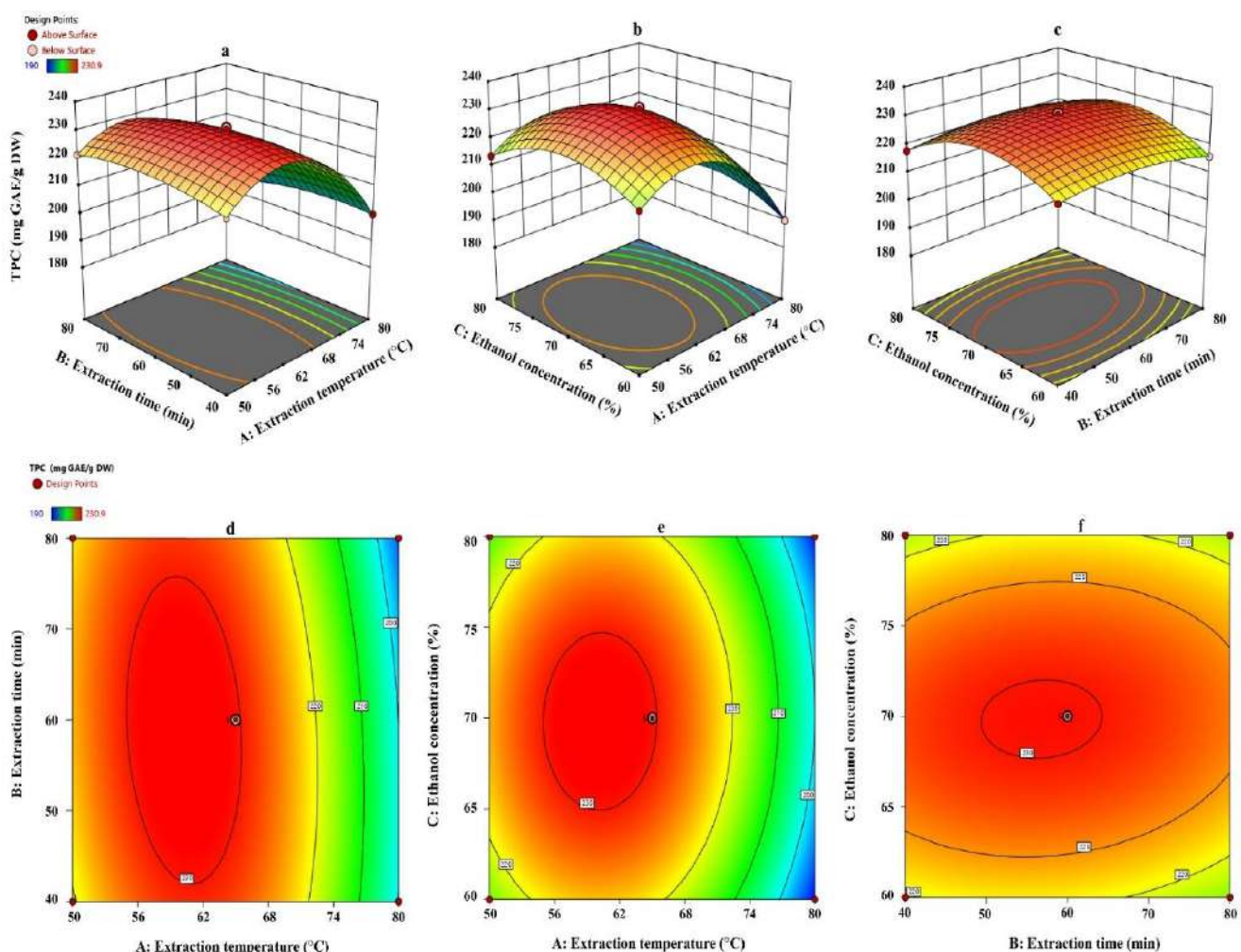


FIGURE 3: The 3D surface plot based on Box-Behnken Design experiment with total phenolic content (mg GAE/g DW) as the response (Y_1).

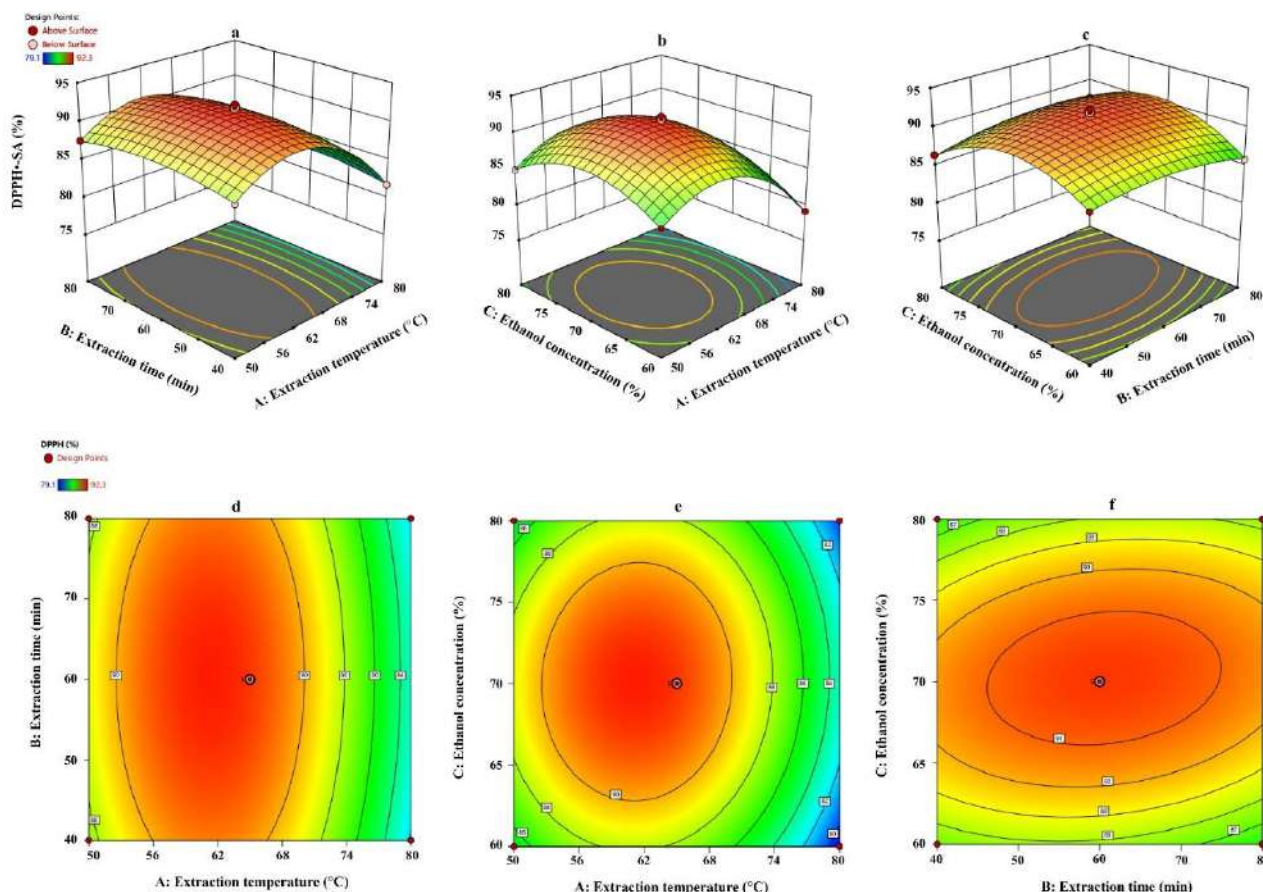


FIGURE 4: The 3D surface plot based on Box-Behnken Design experiment with DPPH•-SA (%) as the response (Y_2).

3.8 Verification of Optimized Conditions:

The optimized extraction conditions predicted by the RSM model were 65°C, 60 min, and 70% ethanol. Under these conditions, the experimental results closely matched the actual and predicted responses, confirming the model's reliability and predictive accuracy. The verified TPC value was 231.8 mg GAE/g DW, closely matching the model values of actual (230.9 mg GAE/g DW) and predicted (230.4 mg GAE/g DW). Similarly, the verified DPPH•-SA% was 91.8%, while the actual and predicted values were 92.3% and 91.6%, respectively. These results further confirm the reproducibility of the experiment. The narrow standard deviations observed across replicates indicate consistent performance and minimal experimental error within the optimized design space. These findings confirm that the model accurately captures the interaction effects among temperature, time, and solvent concentration. The validated conditions provide an effective framework for maximizing phenolic recovery and antioxidant activity from PPE. Furthermore, the optimized parameters can be applied to future scale-up studies or pilot-scale biorefinery processes for sustainable valorization of PPE.

IV. CONCLUSION

This study demonstrates the significant antioxidant activity of polyphenol extraction from pomegranate peel, thereby enhancing the oxidative stability of sunflower oil (SFO). Using RSM and BBD, optimal extraction conditions were identified: 65°C for 60 min with 70% ethanol. These conditions resulted in PPE with a high TPC = 231.8 mg GAE/g DW and potent antioxidant activity as demonstrated by a 91.8% inhibition in the DPPH•-SA assay. PPE's antioxidant activity was comparable to synthetic antioxidants such as TBHQ and BHT, demonstrating its potential as a sustainable, effective natural alternative. Additionally, the inclusion of PPE in SFO significantly extended its shelf life, highlighting its practical application as a natural antioxidant. However, concentrations > 250 µg/g may induce mild pro-oxidant effects, suggesting a concentration-dependent efficacy. These findings underscore the value of PPE as an eco-friendly and efficient source of antioxidants, offering a promising alternative to synthetic preservatives in the food industry. The use of PPE could enhance food safety and preservation while supporting the growing demand for natural ingredients.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ACKNOWLEDGMENT

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Jiang Jinhao (Undergraduate student). Works on eco-friendly approaches in chemistry, using plant-derived compounds to develop functional materials for food and packaging applications. Areas of interest include natural antioxidants, antimicrobial agents, and sustainable biopolymer systems. Research explores nanoemulsion technology, surface-active agents, and precise analytical methodologies. Emphasis is placed on biodegradable films and renewable resources such as starch, proteins, and lignocellulosic materials. The goal is to enhance material performance and promote sustainable solutions in food science.





Effect of Different Levels of Neem Coated Urea on Productivity of Finger Millet (*Eleusine coracana* L. Gaertn)

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Abstract— A field experiment was conducted during the kharif season of 2025 at Krishi Vigyan Kendra (KVK), Anini, Dibang Valley, Arunachal Pradesh, to evaluate the effect of different levels of neem-coated urea (NCU) on productivity of finger millet (*Eleusine coracana* L. Gaertn.) cv. VL Mandua 379. The experiment was laid out in a Randomized Block Design with seven treatments and three replications. Data were analysed via analysis of variance (ANOVA), and treatment effects were evaluated at 5% level of significance. Application of NCU significantly influenced all yield parameters. The treatment T₂ (100% NCU) recorded superior performance in yield attributes, including number of seeds per finger (428) [$F(6,12) = 4.80, p < 0.05$], test weight (3.20 g), finger weight (7.77 g) and finger length (9.77 cm). Similarly, biological yield (7.37 t ha⁻¹) and economical yield (2.85 t ha⁻¹) were significantly higher under T₂ compared to other treatments. Harvest index also differed significantly among treatments [$F(6,12) = 19.77, p < 0.001$]. In conclusion, using 100% neem-coated urea increases yield, economical quality and profitability of finger millet. Such a result advocated the use of NCU as a means to improve nitrogen use efficiency in agriculture, although more multi-location testing is desirable.

Keywords— Finger millet, Neem-coated urea, yield.

I. INTRODUCTION

Finger millet (*Eleusine coracana* L. Gaertn) is a significant nutritious crop that is grown in rain-fed and hilly areas in India including Eastern Himalayan region. It is considered a high-nutritional-value crop due to greater calcium, dietary fiber and amino acids content. Although it thrives in poor fertility status and is climate resilient, the yield of finger millet is low due to poor nutrient management, particularly low nitrogen use efficiency. Nitrogen has a key role in crop growth, productivity and quality. But use of conventional nitrogen fertilizers like urea is often accompanied with significant losses due to volatilization, leaching and denitrification, resulting in poor efficiency of nitrogen use and environmental problems. In regions with high rainfall such as Arunachal Pradesh, these losses are exacerbated, leading to poor crop performance and economic losses.

Neem-coated urea (NCU) has been used successfully to enhance nitrogen use efficiency by prolonging nitrogen release and minimising losses. The coating helps in the slow release of nitrogen and acts as an inhibitor of nitrification and so matches the nitrogen supply to plant needs, so improving nitrogen use efficiency. In many studies, it has been reported that the application of NCU not only increases yield but also grain quality and prevents losses to the environment.

However, limited information is available on the performance of graded levels of neem-coated urea on finger millet in the agro-climatic conditions of the Eastern Himalayan region. Therefore, the present investigation was undertaken to evaluate the effect of different levels of neem-coated urea on productivity, nutritional quality, and economic returns of finger millet.

II. MATERIALS AND METHODS

Site of Experimentation: In *Kharif* 2025, the experiment was carried out in KVK Anini, Dibang Valley, Arunachal Pradesh (28.79° N latitude and 95.90° E longitude), at an altitude of 1600–1968 m above mean sea level. The experimental site falls under the Eastern Himalayan agro-climatic zone and is characterized by humid subtropical climatic conditions with high rainfall and moderate temperature. These conditions are favorable for finger millet cultivation under rainfed conditions but also prone to nitrogen losses through leaching, making it suitable for evaluating the efficiency of neem-coated urea (NCU). The soil was acidic (pH = 3.65) and sandy loam.

Experimental Design and Crop Management: The experiment was carried out in a Randomized Block Design (RBD) comprising seven treatments with three replications. Finger millet variety VL Mandua 379 was used as the test crop due to its adaptability and suitability for hill regions. The field was prepared to a fine tilth through ploughing and leveling, followed by layout as per the experimental design. The treatments consisted of graded levels of nitrogen applied through neem-coated urea, including a control without nitrogen application. The treatment structure included T₀ (control), T₁ (110% recommended nitrogen through NCU), T₂ (100% recommended nitrogen through NCU), T₃ (90% recommended nitrogen through NCU), T₄ (80% recommended nitrogen through NCU), T₅ (70% recommended nitrogen through NCU), and T₆ (60% recommended nitrogen through NCU). Neem-coated urea was top dressed at the designated levels. Random allocation of treatments was done within each replication to reduce the error of experimentation and to compare the effects of treatments. All plots received enriched organic manure (25 kg). Top dressing with neem-coated urea was applied 20 days after transplanting as per the treatments applied. The seeds were first raised in a nursery and transplanted 30 days later with a spacing of 25cm × 15cm. The same crop management practices, such as irrigation, weeding and pest management, were followed for all the treatments for crop growth.

TABLE 1
DETAIL OF THE EXPERIMENT TREATMENT

	Treatments
T ₀	Control
T ₁	110% Neemcoated urea
T ₂	100% Neemcoated urea
T ₃	90% Neemcoated urea
T ₄	80% Neemcoated urea
T ₅	70% Neemcoated urea
T ₆	60% Neemcoated urea

Observations Recorded: Yield attributes such as number of seeds per finger, finger length, finger weight, and test weight were noted from randomly selected plants in every plot.

Economical yield and biological yield were recorded at harvest and expressed in t ha⁻¹. Harvest index (%) was calculated.

All the categories of recorded observations are mentioned in table 2. along with their purpose.

TABLE 2
CATEGORIZATION OF RECORDED OBSERVATIONS

Category	Parameters Included	Purpose
<i>Yield Attributes</i>	Seeds per finger, Test weight, Finger weight, Finger length	Determine yield potential
<i>Yield Parameters</i>	Biological yield, Economical yield, Harvest index	Measure overall productivity

Statistical Analysis: The experimental data were subjected to analysis of variance appropriate for RBD, following standard procedures. The significance of treatment effects was tested using the F-test at the 5% level of probability. Treatment means were compared using Critical Difference (CD), and Standard Error of Mean (SEm) was calculated to assess precision. The total variation was partitioned into components due to treatments, replications, and error, as described by Snedecor and Cochran.

III. RESULTS AND DISCUSSION

The ANOVA revealed that graded levels of neem-coated urea (NCU) exerted a statistically significant influence ($p < 0.05$) on all major yield attributes, and yield parameters of finger millet. The non-significant effect of replication for most traits indicates minimal experimental variability, confirming that the observed differences were primarily due to treatment effects. Similar reliability of field experiments under controlled conditions has been reported by Snedecor and Cochran (1994).

3.1 Yield Attributes:

The response of yield attributes to different levels of nitrogen applied through NCU were strong and statistically significant as indicated by ANOVA on seeds per finger [$F(6,12) = 4.80$], test weight [$F(6,12) = 29.50$], finger weight [$F(6,12) = 35.03$], and finger length [$F(6,12) = 77.69$]. The size of the F-values, especially the test weight, finger weight and finger length indicates that variation induced by treatment was significantly larger than experimental error and is a strong and consistent treatment effect. T_2 (100% NCU) treatment always produced the highest values in all attributes such as seeds per finger (428), test weight (3.20 g), finger weight (7.77 g), and finger length (9.77 cm), whereas the control (T_0) treated values at the lowest. Table 3 shows all the values graphically represented by Figure 1.

The relatively high F-values in the current study may be explained by the fact that the experimental uniformity was maintained well, the treatment was applied and the variability of the environment was minimal, which reduced the error mean square and increased the ability to detect treatment differences. This is also supported by low standard error of difference (SEd), a range of ± 29.77 of the seeds per finger, a range of ± 0.05 of the test weight and a range of ± 0.19 of the finger length, which all indicate high precision of the means of the treatments. Additionally, critical difference (CD) values with probability level of 5% proved the statistical robustness of treatment comparisons. The differences between T_2 and other treatments exceeded the respective CD values (e.g., CD = 10.36 for seeds per finger, 0.12 for test weight, 0.68 for finger weight, and 0.41 for finger length), establishing that the superiority of T_2 was not only numerically higher but also statistically significant.

The only difference between T_2 and other treatments was not only numerically greater but also statistically significant. The enhancement of yield attributes under T_2 can be ascribed to optimum and maintenance availability of nitrogen, which improves vegetative growth, reproductive development and assimilate translocation. Nitrogen abundance enhances a greater chlorophyll abundance and photosynthetic capacity, which all lead to an increase in spikelet fertility and cost-effective formation. Kumar *et al.* (2023) have reported similar findings where the urea coated with neem showed better yield attributes in finger millet. Interestingly T_1 (110% NCU) was not superior in performing compared to T_2 despite the high nitrogen dose.

This implies that the benefits of nitrogen application in excess of the recommended amount does not proportionately increase the yield attributes, and may actually diminish the effectiveness of nitrogen use. Nitrogen excess can cause luxuriant vegetative development at the cost of reproductive development resulting in inefficient assimilate partitioning. This tendency promotes the law of diminishing returns and is matches with the results of Pradhan *et al.* (2015) and Meena *et al.* (2021).

3.2 Yield Parameters:

Both economical yield and biological yield were significantly influenced by NCU levels and ANOVA demonstrated strong treatment effects on both economical and biological yield. The extremely large value of the F-value of biological yield indicates a very strong treatment effect with very small experimental error, indicating that nitrogen levels played a decisive role in biomass production. The highest biological yield (7.37 t ha^{-1}) and economical yield (2.85 t ha^{-1}) was reported under T_2 (100% NCU), followed by T_3 (90% NCU) and T_4 (80% NCU) whereas control treatment reported the lowest yields. Table 3 presents all the values, and the graph (Figure 1) illustrates the data.

TABLE 3
EFFECT OF DIFFERENT LEVELS OF NEEM-COATED UREA ON YIELD AND YIELD ATTRIBUTES

Treatments	Number of Seeds per Finger	Test Weight (g)	Finger Weight (g)	Finger Length (cm)	Biological Yield (t ha ⁻¹)	Economic Yield (t ha ⁻¹)	Harvest Index (%)
T ₀ – Control	300	2.6	3.82	6.17	5.56	2.25	38.74
T ₁ – 110 % NCU	391.67	2.8	6.5	7.13	6.16	2.5	40.67
T ₂ – 100 % NCU	428	3.2	7.77	9.77	7.37	2.85	42.42
T ₃ – 90 % NCU	361.67	3	7.37	8.63	6.71	2.62	41.05
T ₄ – 80 % NCU	347.67	3.15	7.23	8.5	6.35	2.54	40.25
T ₅ – 70 % NCU	323.33	3.02	6.83	8.8	6.26	2.53	40.18
T ₆ – 60 % NCU	310	2.82	6.7	8.03	6.18	2.48	39.67
F-Test	S	S	S	S	S	S	S
SEd (±)	29.77	0.05	0.31	0.19	0.1	0.06	0.36
CD (P = 0.05)	10.36	0.12	0.68	0.41	0.21	0.14	0.8

Summary of Yield Attributes of Finger Millet under Different Levels of NCU

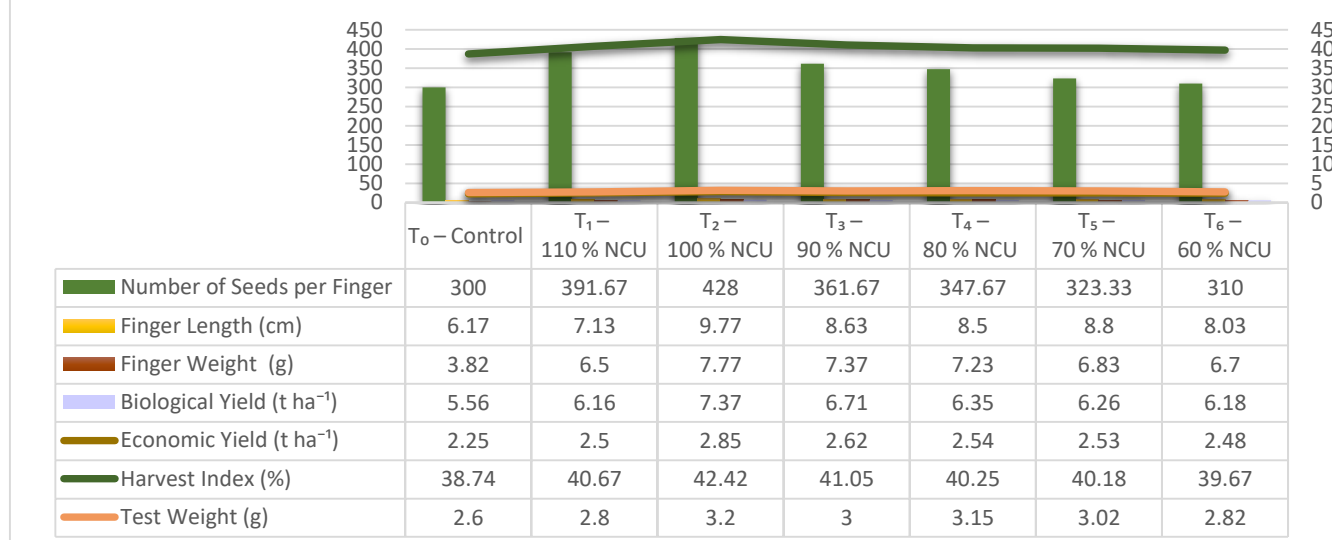


FIGURE 1: Effect of different levels of neem coated urea on yield and yield attributes of finger millet

The high F-values of yield parameters further confirm that the differences in the treatments were not randomly found but a direct cause of the nitrogen management practices. The fact that the SEd of biological yield and economical yield are very low (± 0.10 and ± 0.06) supports the precision of these estimates. Moreover, the calculated values of CD (0.21 in the case of biological yield and 0.14 in the case of economical yield) prove that the yield benefits of T₂ over other treatments were statistically significant as the observed differences were above the level that is required to be considered significant. This supports the accuracy of the treatment ranking, and confirms that T₂ was clearly better in the above experimental conditions. This improvement in yield under T₂ can be explained by two factors; balanced supply of nutrients and higher efficiency of the process of converting assimilates into the economic yield. In addition, the calculated CD values (0.21 for biological yield and 0.14 for economical yield) demonstrate that the yield advantages of T₂ over other treatments were statistically significant, as the observed differences exceeded the threshold required for significance.

The Neem-coated urea controls the release of nitrogen, and the availability of nutrients and crop demand, subsequently reducing the losses due to leaching and volatilization. These results align with Sharma and Singh (2021), who found better nitrogen use efficiency and yield when NCU is applied. The lower yields recorded at the high (110%) and low nitrogen levels further stress the need to optimize the use of nitrogen in agriculture. Harvest index also demonstrated significant variation

[F(6,12) = 19.77), highest value at under T₂ (42.42%). The low SEd (± 0.36) and CD value (0.80) further indicate that the differences in harvest index were accurate and statistically significant which are indicative of optimal partitions efficiencies of optimal nitrogen supply. This has also been observed in cereal crops, which are fed balanced nitrogen nutrition. Similar observations have been reported in cereal crops under balanced nitrogen nutrition (Surekha *et al.*, 2023).

IV. CONCLUSION

The current study has revealed that the use of NCU in management of nitrogen in finger millet under Eastern Himalayan conditions has had significant effects on the yield, quality, and economic payoffs of finger millet. Out of the treatments, the use of 100 percent recommended nitrogen using neem-coated urea (T₂) always registered higher performance in yield. The outcome shows that the optimal supply of nitrogen enhances efficiency in the utilization of nutrients, reduces losses, and increases the partitioning of assimilate to economic yield. Sub-optimal and excessive levels of nitrogen led to poor performance, and therefore, balanced fertilization is crucial. Thus, the use of 100 percent NCU is suggested as an effective and cost-effective measure towards sustainable production of finger millet. It is recommended that further multi-location research is done to confirm these findings in different agro-climatic conditions.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this research paper.

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