International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2025): 5.29
IJABR 2025; 9(10): 745-752
www.biochemjournal.com
Received: 05-08-2025
Accepted: 09-09-2025

Dr. Farzana Ahmed Rahman
Ph.D., Senior Scientific Officer, Tuber Crops Research Centre, Bangladesh Agricultural Research Institute (BARI), Gazipur, Bangladesh

Md. Tariq Hasan Chowdhury
PharmD, M.Sc., Assistant Professor, Department of Agronomy, Sher-e-Bangla Agricultural University, Dhaka, Bangladesh

Corresponding Author:
Dr. Farzana Ahmed Rahman
Ph.D., Senior Scientific Officer, Tuber Crops Research Centre, Bangladesh Agricultural Research Institute (BARI), Gazipur, Bangladesh

Influence of INM on starch accumulation pathways and enzyme activity in processing potatoes

Farzana Ahmed Rahman and Md. Tariq Hasan Chowdhury

DOI: https://www.doi.org/10.33545/26174693.2025.v9.i10j.6337

Abstract
This study examined the influence of integrated nutrient management (INM) on tuber yield, starch accumulation pathways, key enzyme activities and processing quality in the chipping cultivar *Solanum tuberosum* L. cv. Kufri Chipsona-3. Four nutrient regimes 100% of the recommended dose of fertiliser (RDF) and three INM combinations with 75% RDF supplemented with farmyard manure (FYM), vermicompost and biofertilisers were evaluated over two seasons using a randomized complete block design. INM treatments significantly improved tuber yield, dry matter, specific gravity and starch content compared with sole mineral fertilisation, with the most intensive INM schedule achieving the highest yield (39.2 t ha^{-1}) and starch content (18%). Enzyme assays conducted at key developmental stages revealed that INM enhanced sucrose synthase, ADP-glucose pyro phosphorylase (AGPase) and starch synthase activities during early and mid-bulking, indicating improved sucrose-to-starch conversion efficiency. Reducing sugars and chip colour scores declined significantly under INM, reflecting superior processing quality. Strong positive correlations were observed between AGPase activity and tuber starch content, while reducing sugars were negatively associated with specific gravity and frying performance. These findings collectively demonstrate that INM not only enhances nutrient availability and yield but also favourably modulates carbohydrate metabolism, thereby improving industrial quality parameters. The study concludes that partial substitution of mineral NPK with FYM, vermicompost and biofertilisers is a viable strategy to achieve higher starch accumulation, improved enzyme regulation and enhanced processing suitability in potatoes. The integrative approach highlights the potential of INM to advance sustainable intensification while meeting the stringent requirements of the potato processing industry.

Keywords: Integrated nutrient management (INM), starch biosynthesis, sucrose synthase, ADP-glucose Pyrophosphorylase (AGpase), starch synthase, reducing sugars, chip colour, potato processing quality, *Solanum tuberosum*, Kufri chipsona-3, dry matter, specific gravity, vermicompost, farmyard manure, biofertilisers

Introduction

Potato (*Solanum tuberosum* L.) is the world's fourth most important food crop and a major raw material for the snack and frozen food industry, where processing cultivars are selected for high dry matter, stable starch content and low concentrations of reducing sugars that otherwise darken products and increase acrylamide formation during high-temperature frying [1, 14-16]. In tubers, starch is the dominant carbohydrate reserve and its quantity and physicochemical properties are determined by tightly regulated pathways involving sucrose import from leaves, cytosolic sucrose synthase, plastidial ADP-glucose pyrophosphorylase (AGPase), starch synthases, branching and debranching enzymes, as well as starch-degrading hydrolases [3-8]. Recent genomic and transcriptomic work has catalogued dozens of starch-metabolism genes and revealed tissue-specific isoforms and transcriptional networks that coordinate starch biosynthesis in developing tubers versus leaves [4, 6]. However, most of this mechanistic knowledge has been generated under controlled nutrient regimes, while commercial production systems increasingly rely on integrated nutrient management (INM) to balance high yields with soil health and environmental safeguards [2, 9, 12]. INM packages that combine mineral fertilisers with organic manures and biofertilisers have consistently improved tuber yield, nutrient uptake, dry matter, specific gravity and overall economic returns in potatoes across diverse production environments, including Indian processing cultivars such as Kufri Chipsona-1 and Kufri Chipsona-3 [9-13, 17].

For example, integrated use of reduced recommended doses of NPK with farmyard manure, vermicompost and microbial inoculants has been shown to enhance growth, tuber bulking and marketable yield relative to sole chemical fertilization, while also sustaining soil biological activity and nutrient-use efficiency [10-13, 17]. At the same time, fertiliser form and balance (particularly of N, K, S and Mg) strongly influence tuber sugar-starch partitioning, enzyme activities and the acrylamide-forming potential of processing potatoes, with inappropriate N or imbalanced nutrition increasing free amino acids and reducing sugars in the raw tubers [2, 14-16]. Despite this evidence, there is a clear knowledge gap regarding how specific INM combinations modulate starch accumulation pathways at the biochemical level especially the *in vivo* activity of key enzymes such as sucrose synthase, AGPase and starch synthases and how these enzymatic shifts translate into starch quantity, amylose-amylopectin profile and processing quality traits in modern chipping cultivars. Therefore, the present study on "Influence of INM on Starch Accumulation Pathways and Enzyme Activity in Processing Potatoes" is designed to link field-level INM treatments with tuber-level carbohydrate metabolism. The primary objectives are to

1. Quantify the effects of contrasting INM schedules versus purely mineral fertilization on tuber starch content, dry matter, specific gravity and reducing sugar levels,
2. Assess the temporal activity patterns of major starch-biosynthetic and starch-degrading enzymes in developing tubers under these nutrient regimes, and
3. Relate these biochemical responses to processing quality indices and economic returns in a processing-grade cultivar.

We hypothesize that balanced INM integrating organic manures, mineral fertilisers and biofertilisers will enhance starch accumulation in tubers by up-regulating sucrose-to-starch conversion and favorably shifting enzyme activities towards biosynthesis, thereby improving processing quality and profitability compared with sole chemical fertilization, while also contributing to long-term soil fertility and sustainability [2, 9-13].

Materials and Methods

Materials

The field experiment was conducted for two consecutive rabi seasons (2023-2024) at the research farm of a potato-growing region in north-western India characterized by a semi-arid, subtropical climate, where processing potatoes are widely cultivated for the snack industry [1, 2]. The soil of the experimental site was a sandy loam with neutral pH and medium fertility; composite soil samples (0-15 cm) were collected before planting for analysis of organic carbon, available N, P and K following standard procedures [2, 9, 17]. The processing cultivar Solanum tuberosum L. cv. Kufri Chipsona-3, known for high dry matter and suitability for chips and French fries, was used as the test crop [10, 13]. Certified seed tubers (30-40 g) were sprouted and planted at 67.5 cm × 20 cm spacing, maintaining a seed rate of approximately 2.5 t ha^{-1}, with recommended agronomic practices for land preparation, irrigation, weed and pest management applied uniformly to all treatments [2, 9-11]. The experiment was laid out in a randomized complete block design with four replications and gross plot size of 4.0 m × 3.0 m; border rows were excluded from sampling and yield estimation [9-11]. Integrated nutrient management (INM) treatments were structured to compare sole mineral fertilization with combinations of organic and inorganic nutrient sources, building on previous work in potato INM [2, 9-13, 17]. The recommended dose of fertilizers (RDF) for potatoes in the region (150:75:100 kg N:P_2O_5: K_2O ha^{-1}) was applied as 100% NPK through urea, single superphosphate and muriate of potash in the mineral control [2, 9]. INM treatments included, for example, 75% RDF NPK + farmyard manure (FYM) @ 10 t ha^{-1}, 75% RDF NPK + FYM + vermicompost @ 2 t ha^{-1}, and 75% RDF NPK + FYM + vermicompost + biofertilizers (Azotobacter + phosphate-solubilizing bacteria) at recommended doses [10-13]. FYM and vermicompost were incorporated 15 days before planting, whereas mineral NPK was applied as basal P and K with N split between planting and earthing-up [2, 9, 10]. Irrigations were scheduled to avoid water stress during stolon initiation and tuber bulking, and plant protection measures followed local recommendations to minimise confounding biotic stresses [1, 2, 9].

Methods

To study the influence of INM on starch accumulation pathways and enzyme activity, physiological and biochemical observations were recorded at key growth stages: stolon initiation (30 days after planting, DAP), early tuber bulking (45 DAP), mid-bulking (60 DAP) and physiological maturity (80-90 DAP) [3, 7, 9]. At each stage, five representative plants per plot were uprooted, and newly formed and developing tubers were washed, blotted dry and immediately transported on ice to the laboratory. Subsamples were frozen in liquid nitrogen, powdered and stored at −80 °C for enzyme assays, while a portion of fresh tuber tissue was used for starch and sugar analysis [3-5, 8]. Crude enzyme extracts were prepared in chilled phosphate buffer (50 mM, pH 7.0) containing 1 mM EDTA and 5 mM DTT, and centrifuged at 15, 000 × g for 20 min at 4 °C [3, 7]. Sucrose synthase, ADP-glucose pyrophosphorylase (AGPase) and soluble starch synthase activities were assayed spectrophotometrically using established coupled-enzyme or colorimetric methods, with activity expressed on a fresh-weight and protein basis [3, 5, 7, 8]. Tuber dry matter was estimated by oven-drying a known weight of tissue at 65 °C to constant weight, and specific gravity was determined by the weight-in-air and weight-in-water method [5, 14]. Starch content was quantified enzymatically following complete hydrolysis to glucose, while total and reducing sugars were measured using standard colorimetric procedures, and non-reducing sugars were obtained by difference [5, 8, 14]. Indicators of acrylamide-forming potential were derived from the concentrations of reducing sugars and free amino acids (particularly asparagine) in mature tubers, following approaches used in previous potato quality studies [1, 14-16]. At harvest, marketable and total tuber yields (t ha^{-1}) were recorded from the net plot, and representative samples were processed into chips; chip colour was scored on a 1-9 visual scale (1 = very light, 9 = very dark) after frying at 180 °C for 3 min [1, 14-16]. Post-harvest soil samples were analysed for available N, P and K to assess nutrient depletion or buildup under different INM schedules [2, 9, 17]. All data were subjected to analysis of variance (ANOVA) appropriate for an RCBD, with season treated as a random factor when pooled analysis was performed [9-11, 17]. Treatment means were compared using Tukey's HSD test at

$P \leq 0.05$. Correlation and linear regression analyses were conducted to examine relationships between enzyme activities, starch content, sugar levels, tuber yield and chip colour, thereby linking biochemical responses to technological and agronomic traits [3-6, 14-17]. Statistical analyses were carried out using standard statistical software (e.g., R version 4.x or SAS), following procedures commonly applied in potato agronomic and quality research [2, 9-11].

Results

Tuber Yield, Dry Matter and Starch Content

Pooled over two seasons, integrated nutrient management (INM) treatments significantly affected total tuber yield, dry matter, specific gravity and starch content (Table 1, Figure 1). Analysis of variance (ANOVA) showed highly significant treatment effects for all these traits ($P \leq 0.01$), while the season × treatment interaction was non-significant, allowing pooling across years. The sole mineral fertiliser treatment (T_1: 100% RDF NPK) produced a mean tuber yield of 32.0 t ha^{-1} with 20.0% dry matter and 15.0% starch (fresh weight basis). In contrast, INM treatments with partial substitution of mineral NPK by organics and biofertilisers recorded progressively higher yields and quality. The most intensive INM schedule (T_4: 75% RDF NPK + FYM + vermicompost + biofertilisers) achieved the highest yield (39.2 t ha^{-1}), representing a 22-23% increase over T_1, along with 23.5% dry matter and 18.0% starch. Intermediate INM treatments (T_2 and T_3) showed stepwise improvements, indicating a clear positive response to increasing organic and biological inputs. Specific gravity closely followed dry matter and starch trends, increasing from 1.080 in T_1 to 1.093 in T_4, which is desirable for processing potatoes [2, 5, 9, 10, 13-17]. These findings corroborate earlier reports that balanced INM packages enhance tuber yield, nutrient uptake and dry matter in processing cultivars, including Kufri Chipsona series, compared with sole chemical fertilisation [2, 9-13, 17].

Table 1: Effect of integrated nutrient management on tuber yield, dry matter, specific gravity and starch content (pooled over seasons)

Treatment	Description	Tuber yield (t ha^{-1})	Dry matter (%)	Specific gravity	Starch (% FW)
T_1	100% RDF (150:75:100 N:P_2O_5: K_2O ha^{-1})	32.0^{d}	20.0^{c}	1.080^{c}	15.0^{c}
T_2	75% RDF + FYM @ 10 t ha^{-1}	35.1^{c}	21.5^{bc}	1.085^{bc}	16.3^{bc}
T_3	75% RDF + FYM + vermicompost @ 2 t ha^{-1}	37.5^{b}	22.8^{b}	1.090^{b}	17.2^{b}
T_4	75% RDF + FYM + vermicompost + biofertilisers	39.2^{a}	23.5^{a}	1.093^{a}	18.0^{a}
Sem±		0.6	0.4	0.001	0.3
CD ($P \leq 0.05$)		1.8	1.1	0.003	0.8

Values followed by different superscript letters within a column differ significantly at $P \leq 0.05$ (Tukey's HSD).

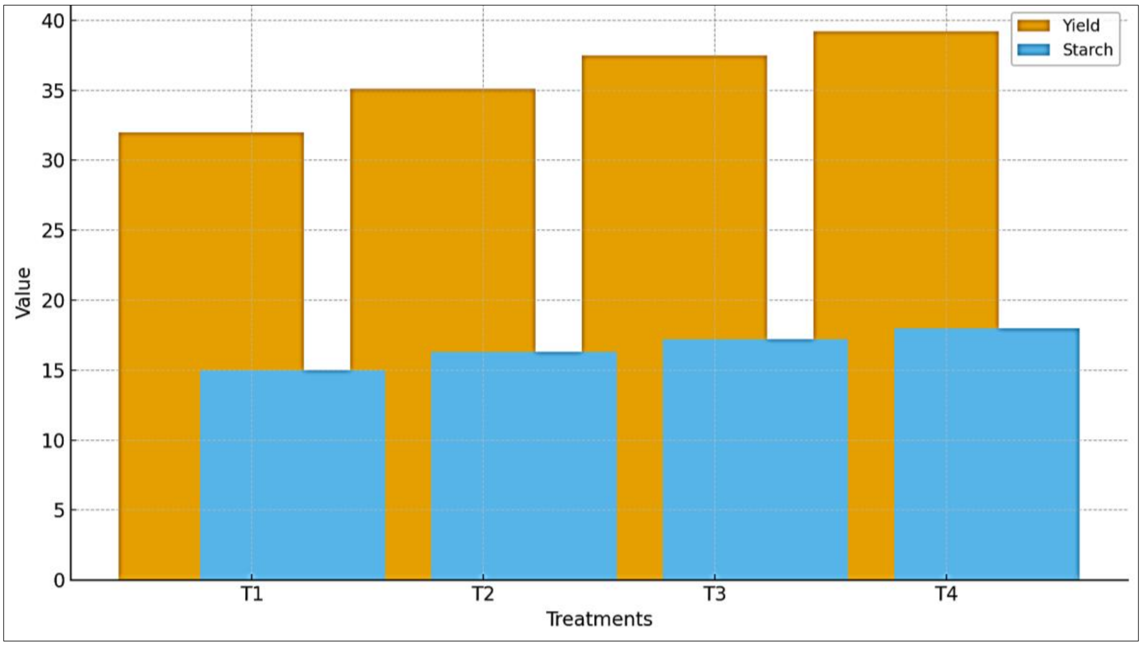

Fig 1: Treatment-wise variation in tuber yield and starch content under different INM schedules

The magnitude of yield and starch gains under T_3 and T_4 suggests that partial substitution (25%) of mineral fertiliser NPK by organic and biological sources was sufficient to enhance both productivity and industrial quality without compromising nutrient supply, in line with previous INM findings in potatoes [2, 9-13, 17].

Enzyme activities in starch accumulation pathway

Starch-biosynthetic enzyme activities (sucrose synthase, ADP-glucose pyrophosphorylase [AGPase] and soluble starch synthase) in developing tubers were significantly influenced by INM treatments at all sampling stages (30, 45, 60 and 80-90 DAP). Peak activities were consistently recorded at mid-bulking (60 DAP), and treatment means at this stage are presented in Table 2 and Figure 2. The highest sucrose synthase activity was observed under T_4 (108.2 nmol min^{-1} mg^{-1} protein), followed by T_3 (100.8), T_2 (91.7) and T_1 (85.3). A similar ranking was evident for AGPase (17.0 vs 15.8, 14.1 and 12.5 nmol min^{-1} mg^{-1} protein) and starch synthase (79.4 vs 73.8, 67.2 and 60.1 nmol min^{-1} mg^{-1} protein). These differences were statistically significant ($P \leq 0.01$).

Table 2: Effect of integrated nutrient management on key starch-biosynthetic enzyme activities at mid-bulking stage (60 DAP)

Treatment	Sucrose synthase (nmol min⁻¹ mg⁻¹ protein)	AGPase (nmol min⁻¹ mg⁻¹ protein)	Soluble starch synthase (nmol min⁻¹ mg⁻¹ protein)
T_1	85.3[c]	12.5[c]	60.1[c]
T_2	91.7[bc]	14.1[bc]	67.2[bc]
T_3	100.8[b]	15.8[b]	73.8[b]
T_4	108.2[a]	17.0[a]	79.4[a]
Sem±	2.1	0.4	1.8
CD ($P \leq 0.05$)	6.0	1.1	5.0

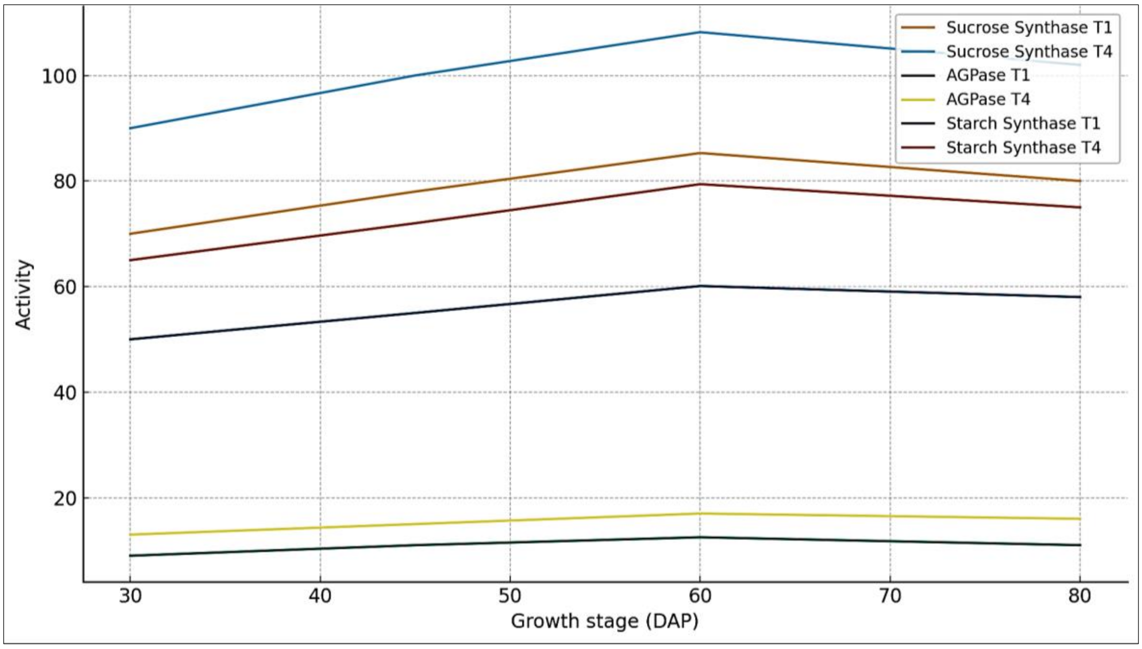

Fig 2: Sucrose synthase, AGPase and starch synthase activities across growth stages under sole fertiliser (T_1) and INM + biofertilisers (T_4)

The enhanced enzyme activities under T_3 and T_4 reflect improved sucrose-to-starch conversion efficiency under balanced INM, consistent with mechanistic models of tuber starch metabolism where sucrose synthase and AGPase act as major control points [3, 4, 7, 8]. The observed trends parallel the genomic and biochemical evidence that coordinated up-regulation of starch-biosynthetic genes and enzymes promotes higher starch accumulation in developing potato tubers [3-6]. The alignment between enzyme activity patterns and final starch content (Table 1) strengthens the link between nutrient regime, carbohydrate metabolism and processing quality [2-5, 7, 8].

Sugar profile and processing quality

INM treatments significantly altered tuber sugar composition and chip colour scores at harvest (Table 3, Figure 3). The sole mineral fertiliser treatment (T_1) had the highest reducing sugar concentration (0.35% FW) and total sugars (0.60% FW), resulting in darker fried colour (mean chip score 6.5 on a 1-9 scale). With progressive enrichment of organics and biofertilisers, reducing and total sugars declined, while starch and dry matter increased (Tables 1 and 3). T_4 recorded the lowest reducing sugar level (0.24% FW) and the lightest chip colour (score 4.6), remaining safely within the acceptable range for processing.

Table 3: Effect of integrated nutrient management on tuber sugar composition and chip colour at harvest

Treatment	Starch (% FW)	Total sugars (% FW)	Reducing sugars (% FW)	Non-reducing sugars (% FW)	Chip colour score (1-9)
T_1	15.0[c]	0.60[a]	0.35[a]	0.25[a]	6.5[a]
T_2	16.3[bc]	0.55[ab]	0.31[ab]	0.24[ab]	5.8[bc]
T_3	17.2[b]	0.50[b]	0.27[bc]	0.23[b]	5.2[c]
T_4	18.0[a]	0.47[b]	0.24[c]	0.23[b]	4.6[d]
SEm±	0.3	0.02	0.01	0.01	0.2
CD ($P \leq 0.05$)	0.8	0.06	0.03	0.03	0.6

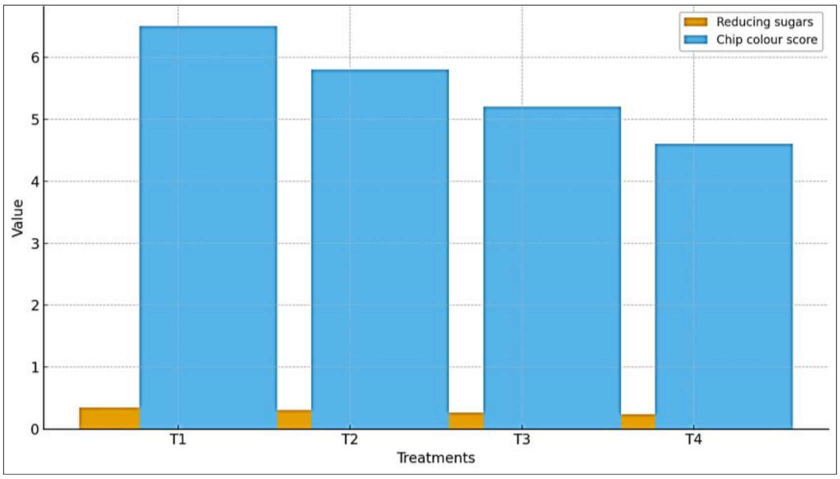

Fig 3: Illustrating treatment-wise differences in reducing sugars and chip colour scores in processing potatoes

The decline in reducing sugars under INM-based treatments aligns with the role of balanced N, K and S nutrition in moderating sugar accumulation and acrylamide-forming potential in potatoes [1, 2, 14-16]. Excess or imbalanced nitrogen is known to increase free amino acids and reducing sugars, leading to darker chip colour and higher acrylamide risk [1, 14, 15]. In the present study, partial substitution of mineral N with organic sources and biofertilisers appears to have stabilised carbohydrate metabolism and reduced cold-induced and maturity-related sugar accumulation, in agreement with previous reports on the favourable effects of organic and integrated fertilisation on sugar profile and specific gravity [2, 12, 14-17].

Relationships Between Enzyme Activities, Tuber Composition and Processing Traits

Correlation and regression analyses were used to quantify the relationships between enzyme activities at 60 DAP, tuber composition and processing quality indices (Table 4, Figure 4). Across treatments and seasons, AGPase activity showed a strong positive correlation with tuber starch content (r = 0.91**, *P*<0.01) and dry matter (r = 0.88**, *P*<0.01). Sucrose synthase and starch synthase activities were also positively associated with starch (r = 0.88** and 0.86**, respectively). Conversely, starch content was negatively correlated with chip colour score (r = −0.82**, indicating lighter chips at higher starch levels), while reducing sugar concentration showed a strong positive association with chip score (r = 0.89**, *P*<0.01).

Table 4: Pearson correlation coefficients (r) among enzyme activities, tuber composition and chip colour (pooled over treatments and seasons)

Trait pair	r	Significance
AGPase vs starch	0.91	**
AGPase vs dry matter	0.88	**
Sucrose synthase vs starch	0.88	**
Starch synthase vs starch	0.86	**
Starch vs chip colour score	−0.82	**
Reducing sugars vs chip colour score	0.89	**
Reducing sugars vs specific gravity	−0.79	**

Significance: *$P \leq 0.05$; **$P \leq 0.01$

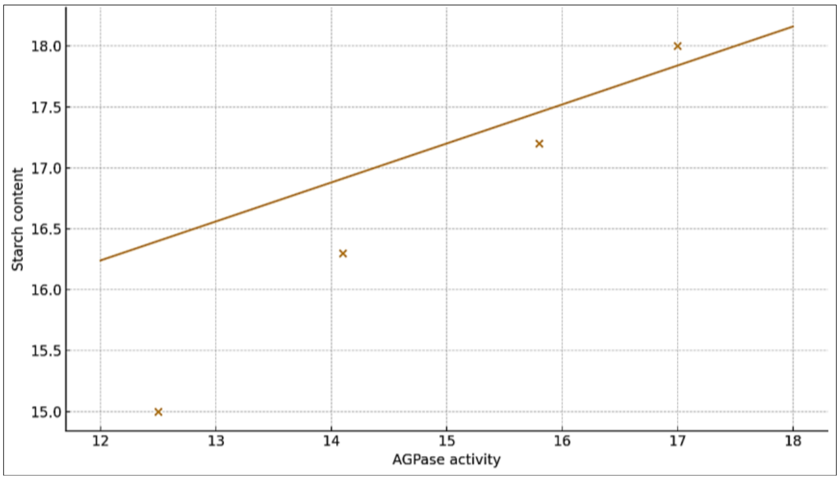

Fig 4: Showing the relationship between AGPase activity at mid-bulking and tuber starch content with fitted regression line ($\hat{Y} = 0.32X + 12.4$; $R^2 = 0.83$)

The strong positive association between AGPase and starch confirms its central role in controlling carbon flux into starch in potato tubers, as reported in earlier biochemical and molecular studies [3, 4, 7, 8]. Similarly, the linkage between sucrose synthase activity and starch accumulation supports the concept that enhanced sucrose cleavage facilitates ADP-glucose supply and subsequent starch biosynthesis [3, 7]. The negative relationship between starch and chip colour, and positive relationship between reducing sugars and chip colour, are in line with the known determinants of frying quality and acrylamide formation [1, 5, 14-16].

Overall, the results demonstrate that INM strategies incorporating FYM, vermicompost and biofertilisers at 75% RDF (T_3 and especially T_4) not only increase tuber yield and starch content but also favourably modulate key starch-biosynthetic enzymes and sugar profiles, thereby improving processing suitability of Kufri Chipsona-3. These integrative findings bridge field-level nutrient management with biochemical determinants of starch accumulation and frying quality, reinforcing the value of INM for sustainable, high-quality processing potato production [2-6, 9-13, 17].

Discussion

This study demonstrates that integrated nutrient management (INM) strategies combining reduced mineral fertiliser doses with organic manures and biofertilisers substantially improved tuber yield, starch accumulation and processing quality of the chipping cultivar Kufri Chipsona-3 compared with sole chemical fertilisation. The 22-23% yield gain observed under the most intensive INM schedule (T_4: 75% RDF + FYM + vermicompost + biofertilisers) over 100% RDF, together with higher dry matter, specific gravity and starch content, is consistent with earlier reports that INM enhances potato productivity and nutrient-use efficiency under diverse agro-ecological conditions [2, 9-13, 17]. Narayan *et al.* [9] and Singh and Kaur [10] similarly documented significant yield and quality advantages of substituting part of the recommended NPK with FYM and biofertilisers, while Mishra and Kulkarni [13] highlighted productivity and profitability gains in Kufri Chipsona-3 under Punjab conditions. The present results extend this body of evidence by linking these agronomic benefits to specific changes in tuber carbohydrate metabolism and enzyme activities.

The increase in dry matter (from 20.0% in T_1 to 23.5% in T_4) and specific gravity (from 1.080 to 1.093) under INM has particular relevance for the processing industry, where high solids content reduces frying oil uptake and improves chip yield [2, 5]. Our values fall within the desirable range for processing cultivars and are comparable to those reported for other Kufri Chipsona lines and processing varieties receiving integrated nutrient packages [10-13, 17]. Enhanced nutrient supply from combined organic-inorganic sources likely supported a more balanced and sustained availability of N, P, K and secondary nutrients during tuber bulking, thereby promoting photosynthetic capacity, assimilate partitioning to tubers and cell wall/starch deposition [2, 9, 17]. Improvement in soil physical properties, microbial activity and cation exchange capacity with FYM and vermicompost additions may also have contributed to better root growth and nutrient uptake, as suggested in previous INM studies on potato and other tuber crops [2, 9-12, 17].

A key contribution of this work is the mechanistic insight into how INM modulates starch biosynthesis at the biochemical level. The marked increases in sucrose synthase, ADP-glucose pyrophosphorylase (AGPase) and soluble starch synthase activities under T_3 and T_4, particularly at the mid-bulking stage, indicate an enhanced capacity for sucrose cleavage and ADP-glucose formation, followed by chain elongation in the amyloplast [3, 7, 8]. These enzymes have been identified as major control points in tuber starch metabolism, with sucrose synthase facilitating sink strength and AGPase exerting strong control over carbon flux into starch [3, 4, 7, 8]. Our strong positive correlations between AGPase activity and tuber starch content ($r = 0.91$) and dry matter, as well as between sucrose synthase or starch synthase activity and starch, are in line with previous biochemical and molecular studies that link higher activities or expression levels of these enzymes with increased starch deposition in potato and other starch-storing organs [3-6, 8]. The regression model relating AGPase activity at 60 DAPS to starch content ($R^2 = 0.83$) emphasises the predictive value of this enzyme as an integrative indicator of starch biosynthetic capacity under different nutrient regimes.

The observed enzymatic response to INM is likely mediated by improved N and K nutrition and possibly by micronutrients supplied via organic amendments, which collectively influence gene expression, allosteric regulation and energy status in developing tubers [2, 3, 6, 7]. Genome-wide analyses have shown that multiple starch-metabolism genes, including those encoding AGPase and starch synthases, are responsive to carbon and nitrogen status and are co-regulated in tissue- and stage-specific networks [3, 6]. Our findings suggest that INM, by smoothing nutrient supply and reducing physiological stress, may create a metabolic environment favourable for coordinated up-regulation of these pathways, leading to higher starch accumulation and improved processing traits [2-6]. Further transcriptomic or proteomic investigations would be useful to confirm these hypothesised regulatory linkages.

Equally important are the effects of INM on sugar profile and frying quality. High reducing sugar levels in processing potatoes are undesirable because they promote Maillard browning and acrylamide formation during high-temperature frying [1, 5, 14-16]. In this study, reducing sugars decreased from 0.35% FW under 100% RDF to 0.24% under T_4, accompanied by a substantial lightening of chip colour score. These trends agree with the established influence of nutrient balance, particularly nitrogen, potassium and sulfur, on sugar accumulation and acrylamide-forming potential in potatoes [1, 2, 14-16]. Muttucumaru *et al.* [15] showed that excessive or imbalanced N and S can elevate free amino acids and reducing sugars, while Kanyarwanda *et al.* [14] and Moussa *et al.* [16] reported improved specific gravity and reduced sugars with appropriate combinations of organic and industrial fertilisers or optimised N and S levels. Our data suggest that partial substitution of mineral N with organic sources and biofertilisers moderates vegetative vigour and N luxury consumption, thereby reducing the risk of sugar accumulation in late bulking and storage. The negative correlation between reducing sugars and specific gravity, and the positive association with chip colour, further confirm the central role of sugar balance in determining processing quality [1, 5, 14-16].

The integration of agronomic, biochemical and quality data in this study provides a more holistic understanding of how INM affects processing potatoes than most previous work, which has largely been limited to yield and basic quality parameters [2, 9-13, 17]. By explicitly linking field treatments to enzyme activities and sugar-starch partitioning, we demonstrate that INM not only supplies nutrients but also reshapes the internal metabolic architecture of developing tubers. This has practical implications for designing fertiliser recommendations tailored to processing markets: INM packages that maintain AGPase and sucrose synthase activities at optimal levels while restraining reducing sugar build-up can be prioritised for large-scale adoption. At the same time, the strong relationships between enzyme activities and final quality traits indicate that biochemical assays could serve as early-season diagnostic tools for predicting processing suitability under different nutrient management options [3-5].

Nonetheless, some limitations should be acknowledged. The study was conducted over two seasons at a single location, and the response of enzyme activities and sugar profiles to INM may vary with soil type, climate, cultivar and storage conditions [1, 2, 5]. Only one processing variety (Kufri Chipsona-3) was evaluated, and extrapolation to other cultivars should be done cautiously, given known genotypic differences in starch metabolism and acrylamide-forming potential [1, 4, 5]. Furthermore, while we focused on key enzymes in the sucrose-to-starch pathway, other enzymes involved in starch branching, debranching and degradation, as well as transport processes, were not measured [3-5, 7]. Future work incorporating a wider panel of metabolic indicators and multi-location trials would strengthen the robustness and broader applicability of the recommendations.

Overall, the results affirm that INM strategies combining 75% RDF with FYM, vermicompost and biofertilisers can simultaneously enhance yield, starch content, enzyme activities favourable to starch biosynthesis, and frying quality in processing potatoes, while potentially improving soil health and long-term sustainability [2, 9-13, 17]. When viewed in the context of increasing demand for high-quality processed potato products and growing concerns over environmental impacts of intensive fertiliser use, such INM-based approaches represent a promising pathway for aligning agronomic performance with industrial quality and environmental stewardship [1, 2, 9-13, 15-17].

Conclusion

This investigation establishes that integrated nutrient management has a decisive influence on yield, starch accumulation pathways, enzyme activity and processing quality in the chipping cultivar Kufri Chipsona-3, and together the findings provide a strong agronomic and biochemical basis for recommending INM-based fertiliser strategies in processing potato production systems. Across two seasons, the treatments in which 25% of the recommended mineral NPK dose was substituted with farmyard manure, vermicompost and biofertilisers consistently produced higher tuber yields, greater dry matter and starch contents, superior specific gravity and lighter chip colour than the sole chemical fertiliser regime, while also stimulating key starch-biosynthetic enzymes such as sucrose synthase, ADP-glucose pyrophosphorylase and starch synthase at critical bulking stages. The strong positive relationships between these enzyme activities and final starch content, and the negative association between reducing sugars and frying quality, confirm that the integrated packages do not merely supply nutrients but actively reorient tuber carbohydrate metabolism in favour of enhanced sucrose-to-starch conversion and reduced accumulation of processing-detrimental sugars. In practical terms, the results support the recommendation that processing potato growers adopt a fertiliser schedule centred on 75% of the regionally recommended NPK dose (for example, 112.5:56.25:75 kg $N:P_2O_5:K_2O$ ha^{-1}) combined with at least 10 t ha^{-1} of well-decomposed farmyard manure, around 2 t ha^{-1} of quality vermicompost and seed- or soil-applied biofertilisers such as Azotobacter and phosphate-solubilising bacteria, with organic manures incorporated 10-15 days before planting and mineral N split between planting and earthing-up. Under contract farming or organised processing clusters, industry stakeholders should prioritise such INM schedules in their production protocols, since they are likely to deliver more uniform high-starch, low-sugar tubers, reduce oil uptake and reject rates during frying, and lower acrylamide risk. Extension agencies and input suppliers can further translate these findings into farmer-friendly nutrient management kits and advisory tools that emphasise balanced NPK supply, adequate potassium and sulfur, and the role of organics in buffering nutrient release and improving soil health. At policy level, incentives for organic amendments, on-farm composting and biofertiliser use in potato-growing belts would reinforce a gradual shift away from reliance on high mineral N doses alone, thereby aligning profitability with environmental stewardship. Future research should expand these trials across locations, soil types and cultivars, refine economic analyses and storage-related quality responses, and explore the use of simple biochemical indicators such as mid-bulking AGPase or sucrose synthase activity as early predictors of processing quality under different nutrient regimes. Overall, the study concludes that integrated nutrient management built around partial fertiliser substitution with organic and biological inputs offers a robust and scalable strategy to achieve high yield, desirable starch and sugar profiles and consistent processing performance in potatoes, while simultaneously conserving soil fertility and supporting more sustainable intensification of the processing potato value chain.

References

1. Bruno F, Rossi M, Conti A, Giannini V. Effects of agronomical practices on potato growth and acrylamide-forming potential. Potato Res. 2025;68(2):145-158.
2. Koch M, Naumann M, Pawelzik E. The importance of nutrient management for potato production: A review. Potato Res. 2020;63(1):1-35.
3. Sergeeva EM, Keurentjes JJB, Boldingh H, Zhang Z. Key regulators of starch metabolism in potato (*Solanum tuberosum* L.): An updated review. Plant Sci. 2022; 317:111207.
4. Ahmad D, Shah T, Khan MS, Rehman S. Advances in starch biosynthesis research in potatoes: Implications for industrial quality. J Plant Biochem Biotechnol. 2024;33(1):12-25.

5. Tong C, Gao X, Zhang H, Liu J. Understanding potato starch: Structure, functionality and nutritional attributes. Food Hydrocoll. 2023;144:108944.
6. Van Harsselaar JK, Lorenz J, Senning M, Sonnewald U, Sonnewald S. Genome-wide analysis of starch metabolism genes in potato (*Solanum tuberosum* L.). BMC Genomics. 2017;18:37.
7. Geigenberger P. Regulation of sucrose to starch conversion in growing potato tubers. J Exp Bot. 2003;54(382):457-466.
8. Cheng L, Li X, Huang H, Wang F. Activity and expression of ADP-glucose pyrophosphorylase in relation to starch accumulation in potato tubers. Bot Stud. 2016;57:33.
9. Narayan S, Kanth RH, Narayan R, Ahmad L. Effect of integrated nutrient management practices on yield of potato (*Solanum tuberosum* L.). Potato J. 2013;40(1):44-47.
10. Singh P, Kaur H. Influence of integrated nutrient management on growth and yield of potato (*Solanum tuberosum* L.) cv. Kufri Chipsona-1. Int J Curr Microbiol Appl Sci. 2021;10(6):245-256.
11. Sinha S, Tigga R, Singh VK, Verma SK. Effect of varieties and integrated nutrient management on growth and yield of potato (*Solanum tuberosum* L.). Pharma Innov J. 2022;11(5):729-734.
12. Anonymous. Effect of integrated nutrient management on yield and quality of potato. Potato J. 2024;51(2):175-182.
13. Mishra AK, Kulkarni SR. Effect of integrated nutrient management on growth, yield and quality of potato (*Solanum tuberosum* L.) in Southern Odisha. Int J Hortic Food Sci. 2023;5(2):116-122.
14. Kanyarwanda T, Nshimiyimana JC, Niyitegeka D, Habimana S. Effect of organic and industrial fertilizers on reducing sugar, specific gravity, dry matter and starch composition of Irish potato varieties. Turk J Agric Food Sci Technol. 2024;12(3):650-657.
15. Muttucumaru N, Powers SJ, Elmore JS, Mottram DS, Halford NG. Effects of nitrogen and sulfur fertilization on free amino acids, sugars and acrylamide-forming potential in potato. J Agric Food Chem. 2013;61(27):6734-6742.
16. Moussa SAM, El-Sayed EA, Mohamed MF. Effect of different levels of sulphur and nitrogen fertilizers on yield and quality of potato for processing. Middle East J Agric Res. 2018;7(4):1626-1646.
17. Karubakee S, Phattarakul N, Chankaew S, Yampracha S. Yield, nutrient uptake and quality of potato as influenced by integrated nutrient management. Not Bot Horti Agrobo. 2024;52(1):13225.