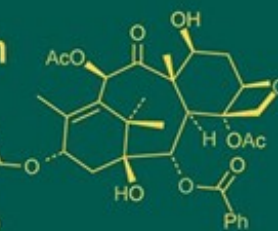
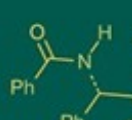


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Influence of Altitudinal Gradients on the Morpho-Physiological and Biochemical Quality Profiles of Pineapple (*Ananas comosus* L. Merr.) in Meghalaya, India

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ABSTRACT

Altitude can shape fruit development by altering the thermal and radiation environment in which a crop grows. This is particularly relevant in Meghalaya, where pineapple is cultivated across a pronounced topographic gradient. The present study evaluated mature pineapple (*Ananas comosus* L. Merr.) fruits collected from three altitude classes: low altitude (<300 m above mean sea level, amsl; Zone A), mid altitude (300–700 m amsl; Zone B), and high altitude (>700 m amsl; Zone C). Five physical traits—total fruit weight, fruit weight without crown, fruit length, fruit diameter and peel percentage—and six biochemical traits—total soluble solids (TSS), pH, titratable acidity, vitamin C, total sugars and β-carotene—were compared. All traits differed significantly among the altitude zones ($p < 0.001$). Zone B produced the largest fruits, with total fruit weight of 1519 g, crown-free weight of 1261 g, length of 20.87 cm and diameter of 13.11 cm. The same zone recorded the highest TSS (15.07 °Brix), vitamin C (39.80 mg/100 g), total sugars (9.62%) and β-carotene (0.12 mg/100 g). Zone C produced substantially smaller fruits and had lower TSS, sugars, vitamin C and β-carotene, while titratable acidity increased to 0.84%. Pearson correlation analysis showed strong positive relationships among fruit size traits and significant positive relationships between fruit size and several biochemical attributes. Titratable acidity showed strong negative associations with fruit size, TSS, total sugars and β-carotene. Peel percentage was comparatively weakly related to the major fruit-size traits. Overall, the mid-altitude environment provided the most favourable combination of marketable fruit size and measured biochemical quality under the conditions represented by the study. The findings support altitude-sensitive pineapple planning in Meghalaya while also indicating the need to integrate elevation with soil, climate, cultivar and management information in future site-specific recommendations.

Keywords: Pineapple, *Ananas comosus*, Altitude, Meghalaya, Fruit quality, Total soluble solids, Titratable acidity, Total sugars, Vitamin C, B-carotene, Pearson correlation

1. Introduction

Pineapple (*Ananas comosus* L. Merr.) is an economically important tropical fruit crop whose value is determined by a combination of yield, fruit size, eating quality and nutritional composition. The crop is consumed fresh and is also used in juice, canning, dehydration, preserves and several other processed products. In practical terms, growers and buyers rarely judge a pineapple using a single attribute. A large fruit may be attractive in the market, but its commercial value is influenced by edible yield, soluble solids, acidity, sugar concentration, colour, aroma and nutritional quality. For this reason, studies that examine fruit weight together with biochemical characteristics provide a more meaningful picture of production performance than studies based only on yield.

The growing environment is one of the major sources of variation in fruit quality. Temperature, radiation, moisture availability and atmospheric conditions influence the rate of vegetative growth, flowering, fruit development and biochemical accumulation. These factors are especially important in mountainous regions, where elevation changes over relatively short distances. In such landscapes, two orchards located only a few kilometres apart can experience different thermal regimes and radiation environments. Altitude therefore provides a useful starting point for identifying contrasting production environments, although it should not be considered an isolated causal variable.

Meghalaya provides an appropriate natural setting for studying these relationships. The state has a highly varied topography, substantial rainfall and a long tradition of horticultural production.

Pineapple is among the important fruit crops of Meghalaya, and the state agriculture department reports that it is grown from the plains to about 1000 m above mean sea level, with particularly favourable performance

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in foothill areas up to around 700 m. Giant Kew is reported as the most prominent variety, followed by Queen. This production pattern makes elevation a practically relevant factor for pineapple planning in the state rather than merely an academic environmental gradient (Department of Agriculture, Government of Meghalaya, n.d.).

Elevation affects several environmental variables simultaneously. Temperature normally declines with increasing elevation, while atmospheric pressure and, depending on local conditions, humidity and radiation characteristics also change. The consequences for plants are complex. Cooler conditions can slow biochemical reactions and cell expansion, whereas excessive heat can increase respiratory losses and alter water relations. Radiation can influence photosynthetic carbon gain and the synthesis of secondary metabolites. The final fruit phenotype is therefore the result of the balance between carbon acquisition, respiration, translocation, storage and developmental processes. Pineapple has an important physiological advantage in relation to water use because it is a CAM plant. CAM metabolism allows carbon dioxide uptake mainly during the night and helps the plant conserve water under conditions of atmospheric demand. However, CAM physiology does not make the crop independent of temperature. The rate of carbon fixation, enzyme activity and assimilate utilization is still influenced by the thermal environment. The biology and postharvest physiology of pineapple indicate that pre-harvest environmental conditions have an important influence on fruit development and the compositional changes that determine final quality (Lobo *et al.*, 2016) [1].

Fruit development is particularly important because the quality attributes measured at harvest are the end result of processes that occur over an extended period. Cell division and expansion determine much of the final fruit size, while assimilate accumulation contributes to fruit mass and soluble solids. As maturity advances, sugars increase and the relative balance between sugars and organic acids changes. Thus, differences among altitude zones may reflect differences not only in the amount of assimilate produced but also in the timing and rate of fruit development and maturation.

Total soluble solids are widely used as a practical indicator of pineapple maturity and sweetness. Although TSS is not equivalent to sugar concentration, sugars are a major component of the soluble fraction and generally contribute substantially to the measured value. Titratable acidity provides complementary information because organic acids contribute to flavour and determine the balance between sweetness and sourness. Research on pineapple organic acid metabolism has shown that acidity changes substantially during fruit development and that citric acid is a major contributor to the acid fraction. The sugar-to-acid balance is therefore an important component of eating quality (Chan *et al.*, 2007).

Recent biochemical and molecular studies have reinforced the importance of coordinated sugar and acid metabolism in pineapple. Metabolomic and transcriptomic investigations have linked sucrose accumulation with several metabolic and transport pathways and have shown that citric acid accumulation is controlled through interacting biochemical routes. These findings provide a useful framework for interpreting field observations: an environmental factor such as altitude may influence fruit quality through multiple metabolic pathways rather than through one isolated process. Therefore, an observed change in TSS or acidity should be considered as part of a broader biochemical response.

Nutritional traits add further value to the assessment. Pineapple contains vitamin C and other bioactive compounds, and the fruit is increasingly considered not only a source of energy and flavour but also a component of a health-oriented diet. Reviews of pineapple composition have highlighted the contribution of vitamins, minerals, dietary fibre and bioactive compounds to the nutritional value of the fruit. They also emphasize that cultivar, maturity, climate and postharvest handling can influence the final composition. Consequently, a produc-

tion environment that promotes fruit growth may also alter nutritional quality, and these responses need to be evaluated together.

Altitude-related differences have been reported in several fruit crops. In mandarin, altitude and maturity have been shown to influence quality characteristics. Studies on guava, mango and walnut have likewise demonstrated that fruit characteristics and biochemical composition can vary with elevation. Importantly, the response is not identical among crops. In some systems, higher elevations may improve certain quality traits, whereas in others they may reduce fruit size or delay maturity. This variability is a reminder that the concept of an “ideal altitude” is crop- and location-specific.

Evidence is also emerging for pineapple itself. A recent study of honey pineapple reported altitude-related differences in fruit quality and found favourable fruit weight and soluble solids at an intermediate elevation. The study provides useful comparative evidence because it demonstrates that an intermediate environment can support a combination of desirable fruit attributes. However, the production environment, cultivar and elevation classes differed from the present study. The results therefore support the general hypothesis of an altitude response without providing a direct benchmark for Meghalaya.

The present study was undertaken against this background to examine whether the same general pattern occurs in pineapple cultivated across contrasting elevations in Meghalaya. The focus was deliberately placed on a group of traits that represent both marketable fruit size and biochemical quality. Total fruit weight and crown-free weight provide information on production and usable fruit mass; length and diameter describe fruit form; peel percentage provides an indication of non-edible structural mass; and TSS, pH, titratable acidity, vitamin C, total sugars and β -carotene provide complementary information on sweetness, acidity and nutritional quality.

A further objective was to examine the relationships among these traits. Correlation analysis is useful because fruit attributes do not operate independently. For example, a larger fruit may also contain more total sugars, while acidity may vary in the opposite direction. Understanding these relationships helps explain the overall quality pattern and can identify traits that provide overlapping information. However, correlation should be interpreted carefully: a strong association does not prove that one trait causes a change in another.

The study was therefore designed with three broad aims: first, to compare the physical characteristics of mature pineapple fruits across low-, mid- and high-altitude zones; second, to compare their biochemical quality; and third, to quantify the associations among the measured traits. The working expectation was that the mid-altitude environment would provide a favourable balance of temperature and radiation, producing fruit with a desirable combination of size and biochemical quality.

2. Materials and Methods

2.1 Experimental framework and altitude classes

The investigation was conducted in Meghalaya using three predefined altitude classes. Zone A represented low altitude (< 300 m amsl), Zone B represented mid altitude (300–700 m amsl), and Zone C represented high altitude (> 700 m amsl). These classes were selected to create a practical environmental gradient covering the lower, intermediate and higher pineapple-growing landscapes of the state. The classification also fits the broad production range described by the state agriculture department, which notes pineapple cultivation from the plains to approximately 1000 m amsl.

The altitude classes should be understood as environmental categories rather than experimental treatments imposed on plants. In a field comparison of this type, elevation is accompanied by changes in temperature, radiation, slope, soil and other environmental factors. The objective was consequently to compare the performance of pineapple fruit under naturally occurring production environments rather than to attribute every difference to elevation alone.

2.2 Fruit sampling and sample handling

Fully mature and apparently uniform pineapple fruits were collected randomly from different parts of Meghalaya within the three designated altitude zones. Fruits with visible mechanical damage or disease symptoms were excluded. The selected fruits were transported to the laboratory under ambient conditions for analysis. The use of mature

fruits was important because many quality parameters change substantially during fruit development and ripening.

Uniformity at sampling was considered particularly important for biochemical comparisons. If fruits at different maturity stages are mixed, differences in TSS, acidity and sugars can become larger than the environmental effect being investigated. The sampling approach therefore attempted to minimize obvious maturity and physical-quality variation before laboratory analysis.



Figure 1. Pineapple Fruit Samples

2.3 Measurement of physical attributes

Total fruit weight was recorded using a digital electronic balance. Fruit weight without crown was measured after removing the crown so that the mass of the fruiting portion could be considered separately. This distinction is useful in commercial evaluation because the crown contributes to total harvested mass but is generally not part of the edible fruit.

Fruit length was measured along the longitudinal axis using a digital Vernier caliper, while fruit diameter was measured across the equatorial region. Together, these measurements provided a simple description of fruit geometry. Peel percentage was calculated from the weight of peel relative to total fruit weight and expressed as a percentage. The measurements were considered collectively because no single physical parameter can adequately represent fruit quality.

2.4 Measurement of biochemical attributes

Total soluble solids were measured using a digital temperature-compensated hand refractometer and expressed as °Brix. The use of temperature compensation is important because refractive index is temperature-sensitive. TSS was treated as an indicator of soluble matter and a practical proxy for sweetness-related maturity status.



Figure 2. Measurement of total soluble solids (TSS) using a hand refractometer

Juice pH was measured using a calibrated digital pH meter. Titratable acidity was determined by titration of filtered pineapple juice using the analytical procedure described in the original study, with phenolphthalein used as the indicator and was expressed as percentage acidity. pH and titratable acidity were interpreted together because they describe different properties of the juice and can respond differently to changes in acid concentration.



Figure 3. Measurement of juice pH using a calibrated digital pH meter

Vitamin C was determined using the DCPIP dye-titration method and expressed on a fresh-weight basis. This parameter was included because ascorbic acid is an important nutritional constituent and an antioxidant. Total sugars were estimated by the phenol-sulfuric acid method of Dubois *et al.* (1956) [2], a widely used colorimetric procedure for total carbohydrate estimation.

β -Carotene was extracted using organic solvents and quantified spectrophotometrically on a fresh-weight basis. The inclusion of β -carotene provided an additional nutritional and pigment-related indicator. Together, vitamin C and β -carotene broadened the assessment from conventional horticultural quality to nutritional composition.

2.5 Statistical analysis

The observations were subjected to one-way analysis of variance under a completely randomized design framework. Altitude zone was considered the treatment factor. Mean comparisons were performed using the procedure specified in the original analysis and statistical significance was interpreted using the probability levels associated with the reported *F*-values. The analysis showed $p < 0.001$ for every physical and biochemical trait evaluated.

Pearson correlation coefficients were calculated for all pairs of measured traits. The correlation coefficient describes both the direction and strength of linear association. Positive values indicate that two variables tend to increase together, whereas negative values indicate an inverse relationship. Significance was denoted by one asterisk for $p < 0.05$ and two asterisks for $p < 0.01$; NS indicated a non-significant relationship. The correlation analysis was used to complement, rather than replace, the analysis of variance.

3. Results and Discussion

3.1 Variation in fruit size and external characteristics

All five physical traits showed significant variation among the altitude zones. The response of fruit weight was especially pronounced. Zone B produced the highest total fruit weight at 1519 ± 18.86 g, compared with 1287 ± 18.86 g in Zone A and 918.40 ± 18.86 g in Zone C. Relative to Zone A, the mid-altitude fruits were approximately 18% heavier, while they were approximately 65% heavier than

the high-altitude fruits. The difference was supported by an *F*-value of 258.27 and a probability value below 0.001.

Fruit weight without crown followed exactly the same ranking. Zone B recorded 1261 ± 13.52 g, Zone A 1068 ± 13.52 g and Zone C 753.37 ± 13.52 g. The similarity of the two patterns is meaningful. If the difference in total weight had been mainly associated with crown development, the crown-free weight would not necessarily have followed the same ranking. Instead, the large difference in crown-free weight indicates that the fruiting structure itself developed more strongly in the mid-altitude environment.

The length and diameter data provide further support. Fruit length was 18.90 ± 0.15 cm in Zone A, 20.87 ± 0.15 cm in Zone B and 15.18 ± 0.15 cm in Zone C. Fruit diameter was 11.95 ± 0.09 cm, 13.11 ± 0.09 cm and 10.16 ± 0.09 cm, respectively. Thus, the mid-altitude fruits were both longer and thicker, whereas the high-altitude fruits were smaller in both dimensions.

The simultaneous increase in length and diameter suggests that the higher fruit weight in Zone B was not due to an isolated change in one dimension. Rather, the whole fruit developed more fully. This interpretation is consistent with the strong correlations among fruit weight, fruit length and fruit diameter observed in the correlation analysis. Fruit weight was correlated with length at $r = 0.88$ and with diameter at $r = 0.90$, while length and diameter were correlated at $r = 0.92$.

The biological explanation for the mid-altitude advantage is likely to involve several interacting factors. A moderate thermal environment can support metabolic activity and cell expansion without imposing excessive respiratory demand. In high-altitude environments, cooler conditions may reduce the rate of biochemical reactions and prolong the time required to accumulate dry matter and structural biomass. The smaller fruits in Zone C are therefore consistent with slower developmental rates. However, because temperature and radiation were not directly measured in the study, these mechanisms remain interpretive rather than experimentally demonstrated.

The low-altitude fruits were larger than the high-altitude fruits but smaller than the mid-altitude fruits. This intermediate position suggests that warmer conditions at low altitude were not sufficient by themselves to maximize fruit development. Under warmer conditions, respiratory activity may increase, potentially reducing the amount of assimilate available for fruit growth. The result illustrates why the response to elevation should not be assumed to be linear. A crop may perform best within an environmental window rather than at the warmest or coolest end of the gradient.

Peel percentage displayed a different pattern. Zone A had the lowest value, $17.87 \pm 0.29\%$, whereas Zone B and Zone C recorded $20.18 \pm 0.29\%$ and $19.60 \pm 0.29\%$, respectively. Zone B and Zone C were statistically similar. This indicates that the larger fruit in Zone B did not necessarily have the lowest proportion of peel. From a processing perspective, this distinction is important. Total fruit weight is useful for yield assessment, but edible recovery is more directly related to crown-free weight, flesh weight and the proportion of non-edible tissues.

The physical results have a direct market implication. Pineapple fruit size affects visual attractiveness, grading and the potential quantity of material available for fresh consumption or processing. The mid-altitude zone produced fruits of approximately 1.5 kg, which is within the broad commercial size range reported for pineapple fruit quality studies. However, market preference varies with cultivar and destination, so size alone should not be interpreted as a universal quality standard.

Table 1. Altitude-wise variation in physical parameters of pineapple fruit.

Altitude zone	Total fruit weight (g)	Fruit weight without crown (g)	Fruit length (cm)	Fruit diameter (cm)	Peel (%)
Zone A (Low)	1287 ^b ± 18.86	1068 ^b ± 13.52	18.90 ^b ± 0.15	11.95 ^b ± 0.09	17.87 ^a ± 0.29
Zone B (Mid)	1519 ^c ± 18.86	1261 ^c ± 13.52	20.87 ^c ± 0.15	13.11 ^c ± 0.09	20.18 ^b ± 0.29
Zone C (High)	918.40 ^a ± 18.86	753.37 ^a ± 13.52	15.18 ^a ± 0.15	10.16 ^a ± 0.09	19.60 ^b ± 0.29
CV (%)	8.31	7.20	4.35	7.78	5.51
F-value	258.27	359.65	394.78	294.51	17.49
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Values are mean ± SE. Different superscript letters within a column indicate significant differences according to the mean-comparison procedure used in the original analysis.

3.2 Variation in TSS, pH and titratable acidity

The biochemical analysis showed significant differences in all measured attributes. TSS was 14.63 ± 0.15 °Brix in Zone A, 15.07 ± 0.15 °Brix in Zone B and 12.96 ± 0.15 °Brix in Zone C. The high-altitude reduction was therefore clear. The mid-altitude value was only slightly higher than the low-altitude value, and both were statistically grouped together in the original table, but the difference between these two zones was much smaller than the reduction observed at high altitude.

The TSS result is important because it indicates that the large fruit produced in Zone B did not have diluted soluble solids. On the contrary, the largest fruits also had the highest TSS. This combination is commercially attractive because growers generally prefer a balance of fruit size and sweetness. The result also corresponds with the total sugar data, which showed the highest concentration in the same zone. The lower TSS at high altitude can be interpreted in relation to temperature-dependent metabolic activity. Sugar accumulation in fruit is influenced by photosynthetic carbon supply, transport and metabolic conversion. Cooler environments may slow these processes or delay the progression of maturity. However, the study did not follow individual fruits over time, so it cannot determine whether high-altitude fruits would eventually reach similar TSS if left longer on the plant. A maturity-stage experiment would be required to distinguish delayed maturation from an intrinsically lower final TSS.

Juice pH declined progressively with elevation, from 4.14 in Zone A to 4.01 in Zone B and 3.90 in Zone C. At the same time, titratable acidity increased sharply in Zone C. Acidity was 0.57% in Zone A, 0.56% in Zone B and 0.84% in Zone C. This means that the high-altitude fruits had both the lowest pH and the highest titratable acidity.

The acidity response is one of the clearest biochemical effects in the dataset. Zone A and Zone B were similar in titratable acidity, whereas Zone C was distinctly higher. The combination of lower TSS and higher acidity at high altitude would be expected to produce a sharper, less sweet flavour profile. By contrast, Zone B combined the highest TSS with one of the lowest acidity values, suggesting a more favourable sweetness-acidity balance.

Pineapple flavour is strongly influenced by the relative abundance of sugars and organic acids. Earlier studies of pineapple fruit development have shown that organic acid concentrations change during maturation and that citric acid contributes substantially to total acidity. The balance between sweetness and acidity is therefore a useful way to interpret the present findings. The high-altitude fruits appear to have retained more acidity while accumulating less soluble carbohydrate.

It is important, however, not to equate titratable acidity with a single organic acid. Titratable acidity is an aggregate analytical measure. A stronger mechanistic study would quantify citric, malic and other relevant organic acids separately and monitor their changes through fruit development. Such measurements would help determine whether the high-altitude response was primarily associated with increased synthesis, reduced degradation or delayed maturation.

Table 2. Altitude-wise variation in biochemical attributes of pineapple fruit.

Altitude zone	TSS (°Brix)	pH	Titratable acidity (%)	Vitamin C (mg/100 g)	Total sugars (%)	β-Carotene (mg/100 g)
Zone A (Low)	14.63 ^b ± 0.15	4.14 ^c ± 0.06	0.57 ^a ± 0.01	34.06 ^b ± 1.01	7.71 ^b ± 0.09	0.11 ^b ± 0.001
Zone B (Mid)	15.07 ^b ± 0.15	4.01 ^b ± 0.06	0.56 ^a ± 0.01	39.80 ^c ± 1.01	9.62 ^c ± 0.09	0.12 ^c ± 0.001
Zone C (High)	12.96 ^a ± 0.15	3.90 ^a ± 0.06	0.84 ^b ± 0.01	27.96 ^a ± 1.01	6.56 ^a ± 0.09	0.09 ^a ± 0.001
CV (%)	5.74	9.14	18.76	6.37	7.47	6.86
F-value	55.56	54.69	177.76	34.12	298.53	75.29
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Values are mean ± SE. Different superscript letters within a column indicate significant differences according to the mean-comparison procedure used in the original analysis.

3.3 Vitamin C and antioxidant-related attributes

Vitamin C concentration varied significantly among the altitude zones. Zone B recorded the highest concentration, 39.80 ± 1.01 mg/100 g, followed by Zone A at 34.06 ± 1.01 mg/100 g. Zone C had the lowest value at 27.96 ± 1.01 mg/100 g. The mid-altitude value was therefore approximately 17% higher than the low-altitude value and about 42% higher than the high-altitude value.

The higher vitamin C concentration at mid altitude suggests that the same environment favourable for fruit size and sugar accumulation also supported the accumulation or retention of ascorbic acid. Vitamin C is influenced by genetic background, maturity, light environment,

temperature and postharvest handling, so the result should not be attributed to altitude alone. Nevertheless, the consistency of the response across several independent quality traits strengthens the interpretation that Zone B represented a favourable production environment.

The high-altitude reduction in vitamin C is particularly interesting because high elevation can sometimes increase antioxidant compounds in plants as part of a response to environmental stress. The present data show that such a general assumption should not be applied automatically to pineapple fruit. The concentration of a specific antioxidant depends on the balance between synthesis, metabolism, dilution and developmental stage. Without measurements of oxidative stress markers or antioxidant enzyme activities, the present study cannot identify the mechanism.

β -Carotene followed the same overall pattern. Concentration was 0.11 ± 0.001 mg/100 g in Zone A, 0.12 ± 0.001 mg/100 g in Zone B and 0.09 ± 0.001 mg/100 g in Zone C. Although the absolute differences were relatively small, the analysis indicated significant variation. The highest value at mid altitude provides additional evidence that Zone B supported a favourable biochemical environment.

Carotenoids contribute to pigmentation and nutritional quality. Their accumulation can be influenced by developmental stage and environmental conditions, particularly light and temperature. The slightly higher β -carotene concentration in Zone B may therefore reflect a favourable combination of radiation and temperature. Again, this interpretation should be tested in future work through direct measurements of radiation and pigment biosynthesis.

3.4 Total sugars and their relationship with TSS

Total sugars showed one of the strongest altitude effects. Zone B had $9.62 \pm 0.09\%$ total sugars, compared with $7.71 \pm 0.09\%$ in Zone A and $6.56 \pm 0.09\%$ in Zone C. The F -value was 298.53 and $p < 0.001$. The difference between Zone B and Zone C was substantial, showing that the intermediate environment supported considerably greater sugar accumulation.

The similarity between the patterns of TSS and total sugars is biologically meaningful. TSS increased from Zone A to Zone B and then declined at Zone C, while total sugars followed the same direction.

Pearson correlation analysis showed a significant positive association between TSS and total sugars ($r = 0.63$). This indicates that, within the sampled fruits, variation in soluble solids was accompanied by variation in total sugar concentration.

The sugar result is also consistent with fruit size. Total sugars were strongly correlated with fruit weight ($r = 0.84$), fruit weight without crown ($r = 0.84$), fruit length ($r = 0.83$) and fruit diameter ($r = 0.83$). These relationships suggest that favourable conditions for fruit growth were also associated with greater sugar accumulation. One possible explanation is that greater assimilate supply supported both structural growth and soluble carbohydrate storage. Another possibility is that the same environmental conditions promoted faster or more complete maturation.

The high-altitude reduction in sugar concentration may therefore contribute to the lower TSS and less favourable flavour balance observed in Zone C. The results support the view that temperature-related developmental differences can influence the final composition of fruit. However, because total sugars were measured as a bulk biochemical variable, the study cannot determine whether the differences were driven mainly by sucrose, glucose, fructose or other soluble carbohydrates. Future studies should quantify individual sugars to provide a more detailed explanation.

3.5 Correlation structure among fruit quality traits

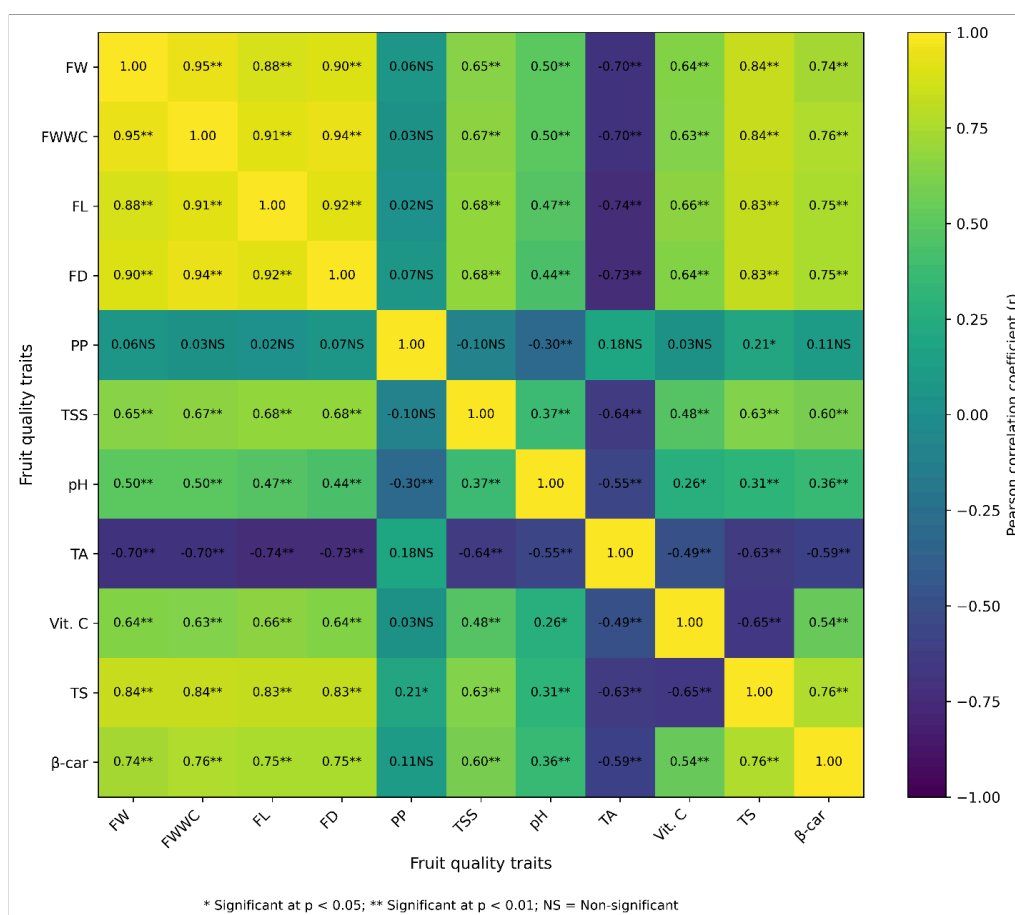


Table 3. Pearson correlation matrix among physiological and biochemical attributes.

The Pearson correlation matrix revealed a coherent network of relationships. The strongest positive association was between total fruit weight and fruit weight without crown ($r = 0.95$). This is expected because the two variables represent closely related measures of fruit mass. Fruit weight was also strongly correlated with fruit length ($r = 0.88$) and fruit diameter ($r = 0.90$). The relationships among FWWC, FL and FD were similarly high, ranging from $r = 0.91$ to $r = 0.94$. The physical-quality network extended into the biochemical traits. Fruit weight was positively associated with TSS ($r = 0.65$), vitamin C ($r = 0.64$), total sugars ($r = 0.84$) and β -carotene ($r = 0.74$), all significant at $p < 0.01$.

Fruit length and diameter showed similar relationships. These findings support the altitude-wise results because Zone B simultaneously recorded the largest fruits and high concentrations of several biochemical constituents.

Titrateable acidity was the most consistently negative variable in the correlation matrix. It was negatively correlated with fruit weight ($r = -0.70$), fruit weight without crown ($r = -0.70$), fruit length ($r = -0.74$), fruit diameter ($r = -0.73$), TSS ($r = -0.64$), vitamin C ($r = -0.49$), total sugars ($r = -0.63$) and β -carotene ($r = -0.59$). The negative association with TSS and total sugars is especially relevant to

flavour because it indicates that fruits with higher sweetness-related measures tended to have lower titratable acidity in the dataset.

pH showed moderate positive correlations with the physical traits and TSS, but a significant negative relationship with titratable acidity ($r=-0.55$). This is consistent with the expected chemical relationship between hydrogen-ion activity and acid concentration, although pH and titratable acidity should continue to be interpreted as distinct measures.

Vitamin C showed positive relationships with fruit weight, length, diameter, TSS and β -carotene. Its strongest negative relationship was with total sugars ($r=-0.65$). This inverse association is interesting because vitamin C and total sugars both peaked at mid altitude. It demonstrates why correlation across individual observations should not be interpreted solely from treatment means. Two traits can both be higher in one altitude zone while still showing a negative relationship across individual observations.

Peel percentage was relatively independent of the main fruit-size traits. Its correlations with fruit weight, fruit weight without crown, fruit length and diameter were 0.06, 0.03, 0.02 and 0.07, respectively, and were non-significant. This suggests that peel proportion was not simply a function of fruit size. Its negative correlation with pH ($r=-0.30$) was significant, while its association with total sugars was small but significant ($r = 0.21$). These relationships should be treated cautiously because they are weaker than the major correlations in the dataset.

The heatmap provides an effective way to communicate the correlation structure because the positive and negative associations can be recognized immediately. The strong positive block among fruit dimensions is visually distinct, while the negative band associated with titratable acidity is equally apparent.

3.6 Interpretation of the mid-altitude advantage

One of the most important outcomes of the study is that the mid-altitude zone was not superior in only one variable. It recorded the maximum for total fruit weight, fruit weight without crown, length, diameter, TSS, vitamin C, total sugars and β -carotene. It also maintained low titratable acidity. This combination makes the result more meaningful than a simple comparison of yield.

The intermediate optimum can be interpreted through the concept of environmental balance. At high altitude, lower temperatures may constrain metabolic activity and delay development. At low altitude, warmer conditions may favour growth but may also increase respiratory losses or create other environmental stresses. The mid-altitude environment may provide sufficient warmth for active growth while avoiding the stronger constraints present at either end of the gradient.

The interpretation is consistent with the state-level recommendation that pineapple performs well in foothill environments up to around 700 m, but the present study adds a biochemical dimension to that observation. The state recommendation is based on broader crop performance, whereas this study demonstrates that intermediate elevations also produced favourable fruit quality under the sampled conditions.

The result should nevertheless be applied carefully. Meghalaya contains substantial variation in slope, aspect, rainfall, soil depth, drainage and management. A 500 m orchard on a south-facing slope may not have the same microclimate as a 500 m orchard on a shaded slope. Likewise, cultivar and planting material can influence fruit size and biochemical composition. Therefore, altitude is best regarded as one layer of a broader site-suitability assessment.

3.7 Implications for pineapple production in Meghalaya

The findings have direct implications for crop planning. Where farmers have flexibility in selecting new pineapple sites, mid-altitude areas within the studied range may deserve priority if the objective is to produce large fruits with favourable sweetness and nutritional attributes. This does not mean that low- or high-altitude areas are unsuitable. Instead, it indicates that their production potential and quality profile may differ and should be evaluated separately.

For low-altitude orchards, the intermediate fruit size and biochemical profile observed in the study suggest that management practices should focus on maintaining efficient assimilate accumulation and avoiding excessive heat or water stress. Mulching, appropriate moisture management and balanced nutrition may help stabilize the root-zone environment, although these practices were not tested in the present experiment and therefore should be evaluated before being recommended specifically for altitude management.

For high-altitude orchards, the main challenge indicated by the data is the combination of smaller fruit size, lower TSS and sugars and higher acidity. Site-specific management and cultivar selection may be particularly important in such environments. Harvest timing could also be investigated because some of the biochemical differences may represent delayed maturity rather than permanently lower quality.

The results are relevant to processing as well as fresh consumption. High fruit weight and crown-free weight in Zone B indicate greater raw-material mass per fruit. However, the relatively high peel percentage means that processors should not rely on fruit weight alone when estimating recovery. Future studies should include edible flesh percentage, core weight, juice recovery and processing yield to translate the present findings into an economic framework.

3.8 Limitations and directions for future research

The present work should be interpreted within the limits of its design. The first limitation is that altitude was observed rather than experimentally manipulated. Consequently, the study establishes an association between production environment and fruit characteristics but cannot isolate the independent effect of temperature, radiation, rainfall or soil properties.

A second limitation is the absence of continuous microclimate observations from each orchard. Direct monitoring of air temperature, canopy temperature, solar radiation, relative humidity and soil moisture would allow the biological interpretation to move beyond altitude categories. Such data could also reveal whether particular climatic thresholds are more strongly associated with fruit quality than elevation itself.

A third limitation concerns genetic and management variation. Commercial orchards may differ in cultivar, planting material, plant density, fertilizer use, irrigation, flowering management and pest-control practices. These factors can influence fruit size and chemistry. Future studies should either standardize these variables or collect sufficient information to include them in statistical models. This is consistent with the broader fruit-breeding literature, which recognizes that fruit size, sugar content, acidity and other quality traits are polygenic and strongly influenced by environmental conditions and genotype $\times$ environment interactions (Meena *et al.*, 2026) [3].

A fourth limitation is that the study was based on mature fruits sampled at harvest. Repeated sampling from flowering through harvest would provide a stronger understanding of developmental trajectories. Such an approach could distinguish slower maturation at high altitude from genuinely different final biochemical composition.

Future studies should also analyse individual sugars and organic acids. Sucrose, glucose and fructose measurements would clarify the biochemical basis of the TSS response, while citric and malic acid measurements would help explain the acidity pattern. Additional nutritional parameters such as total phenolics, antioxidant capacity and detailed carotenoid profiles could provide a more complete quality assessment.

Another important direction is the integration of field measurements with geospatial analysis. Meghalaya's topography makes GIS-based modelling particularly useful. Elevation can be combined with slope, aspect, temperature, rainfall, soil properties, drainage and land-use information to identify areas that are likely to support both productivity and quality. Such an approach would be especially valuable for climate-resilient horticultural planning.

Non-destructive quality assessment is another promising avenue. Spectroscopy, imaging and computer-vision approaches are increasingly being explored for pineapple quality monitoring. These tech-

nologies could potentially estimate fruit size and internal quality without destructive sampling. Linking such measurements with altitude and microclimate data could create a more efficient system for monitoring fruit quality across large and heterogeneous hill production landscapes.

3.9 Broader significance of the findings

The importance of the present results extends beyond the identification of a favourable altitude band. Pineapple production in hill ecosystems is increasingly required to balance productivity with environmental variability. A production environment that consistently produces large fruit with desirable sweetness and nutritional quality can provide advantages across several stages of the value chain, from farm-level grading to processing and consumer acceptance. The present results indicate that environmental zoning can therefore be used not only for estimating where pineapple can grow, but also for anticipating differences in the quality of the harvested product.

The findings are particularly relevant to climate-resilient horticulture. Temperature variability is expected to become increasingly important in crop production, and hill environments may provide opportunities for farmers to adjust production locations according to changing climatic suitability. However, such adaptation requires evidence on both productivity and quality. A shift to a different altitude may maintain fruit survival but alter maturity period, sweetness or acidity. The present study shows why quality indicators should be included when evaluating climate suitability for fruit crops.

An additional implication concerns the interpretation of “high yield” in horticultural systems. Fruit number and total fruit weight are important, but market value often depends on the quality of each fruit. The mid-altitude fruits in this study combined greater mass with higher TSS and sugars, which is a more useful production outcome than high fruit mass alone. Conversely, high-altitude fruits were smaller and more acidic. This distinction can help extension programmes formulate recommendations that consider market requirements rather than focusing exclusively on biomass production.

The results also support a more integrated approach to future pineapple research in Meghalaya. Altitude can be used as an initial environmental stratification variable, followed by more detailed assessment of soil and climate. For example, two sites within the same elevation class could be compared for slope position, soil organic carbon, pH, available potassium, drainage and radiation exposure. The fruit response could then be modelled against these variables. Such an approach would improve the scientific basis for recommending specific production niches.

From a methodological perspective, combining analysis of variance with correlation analysis proved useful. ANOVA identified which traits differed among the altitude zones, while correlation analysis showed how those traits were related to each other. The two analyses answer different questions and should not be treated as substitutes. The combination is especially valuable in fruit-quality studies because quality is inherently multidimensional. Future work could extend this approach through principal component analysis, cluster analysis or path analysis, provided that the sample size and experimental structure are adequate.

For horticultural extension, the findings can be translated into a simple principle: the best production environment is not necessarily the warmest or the highest location, but the environment in which the crop can maintain an efficient balance between vegetative growth, fruit development and biochemical maturation. In Meghalaya, the intermediate altitude zone examined in this study appears to provide such a balance for the sampled pineapple production system. The recommendation should nevertheless be refined using local climate, soil and management data before being generalized to the entire state.

4. Conclusion

The study demonstrates a clear association between altitudinal production environment and the morpho-physiological and biochemical quality of pineapple fruit in Meghalaya. Among the three evaluated

zones, the mid-altitude environment (300–700 m amsl) produced the most favourable overall combination of traits. Fruits from Zone B had the highest total weight, crown-free weight, length and diameter and simultaneously recorded the highest TSS, total sugars, vitamin C and β -carotene. In contrast, Zone C (> 700 m amsl) produced smaller fruits with lower TSS, total sugars, vitamin C and β -carotene but substantially higher titratable acidity.

The correlation analysis supported the treatment-level observations. Fruit size traits were strongly and positively associated with one another, while total sugars and β -carotene showed strong positive relationships with fruit size. Titratable acidity was negatively associated with most of the major physical and biochemical quality attributes. Peel percentage was comparatively independent of fruit size, highlighting the need to consider edible recovery separately from total fruit weight.

From a production perspective, the results indicate that mid-altitude areas of Meghalaya offer considerable potential for producing pineapple with a favourable balance of marketable size and biochemical quality. The findings also suggest that recommendations for pineapple expansion should consider altitude together with soil, climate, cultivar, slope, aspect and management conditions. Altitude alone should not be treated as a universal prescription.

The study provides a useful foundation for future location-specific pineapple planning in Meghalaya. Integrating fruit-quality observations with geospatial and environmental datasets can help identify production zones that are not only capable of supporting high yield but are also likely to produce fruit with desirable quality and nutritional characteristics. Such an approach would strengthen climate-resilient and precision-oriented horticultural planning in the North-Eastern hill region.

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