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Bangladesh Agricultural University

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# Nutraceutical awareness and usage among Gen Z in Khulna: Perceptions, trends, influencing factors, and problems

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**A B S T R A C T**

The global paradigm regarding diet, health, and disease prevention is shifting globally, driven by rising healthcare costs and the growing prevalence of lifestyle-related chronic conditions, such as diabetes and cardiovascular disease, leading to a shift in consumer behavior from disease treatment toward prevention. This new paradigm is characterized by the rapidly expanding nutraceutical market, which encompasses food-derived products such as dietary supplements and functional foods that have been scientifically validated for health benefits beyond basic nutrition. The Asia-Pacific region, including Bangladesh, is experiencing exponential market growth, fueled by an aging population, demand for natural products, and Gen Z's (mid-1990s to early 2010s) strong focus on wellness and preventive health. However, Gen Z's reliance on digital platforms for health information exposes them to both global trends and potential misinformation. In Bangladesh, a "double burden of malnutrition" coexists with rising Non-Communicable Diseases (NCDs), creating a vulnerable market where minimal regulatory oversight poses a significant public health risk. This study, therefore, aimed to characterize the behavioral drivers and influencers of Gen Z's nutraceutical adoption in Bangladesh, identify critical barriers, and propose evidence-based policy recommendations. Using a quantitative survey, the study found that while a strong baseline health-conscious attitude exists, the high product cost was the most significant barrier. Furthermore, the most severe problems highlighted profound public health implications stemming from an information deficit and regulatory ambiguity, as respondents reported great difficulty in distinguishing genuine from fake products, lacking awareness of potential drug-nutraceutical interactions, and finding reliable information. These findings underscore that product availability is insufficient; consumers require accessible, reliable, and verified information to ensure safe usage. In conclusion, Gen Z in Bangladesh is highly motivated towards preventive health. Still, their engagement with the nutraceutical market is critically hindered by economic barriers and a severe information and trust gap, exacerbated by counterfeit products and a lack of awareness regarding drug-supplement interactions. To transition the local market from a high-risk landscape to a beneficial public health tool, stakeholders must prioritize initiatives that mandate clear and transparent product labeling, launch robust public education campaigns, and institutionalize reliable professional guidance to enhance both product safety and consumer trust, confirming that regulatory clarity and consumer literacy are the foundational steps required.

**Keywords:** Nutraceuticals, Generation Z (Gen Z), Preventive Health, Consumer Behavior, Regulatory Oversight, Information Deficit, Public

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## Introduction

The relationship between diet, health, and disease prevention has undergone a profound transformation in the 21st century. As global healthcare costs rise and the burden of lifestyle-related chronic diseases, such as cardiovascular conditions, diabetes, and obesity, increases, there has been a discernible shift in consumer behavior from disease treatment to disease prevention (WHO, 2020). The paradigm is centrally defined by the burgeoning market of nutraceuticals. Coined from "nutrition" and "pharmaceuticals", nutraceuticals are products derived from food sources that provide extra health benefits in addition to the basic nutritional value found in foods. These products include functional foods, fortified beverages, and dietary supplements containing ingredients like probiotics, omega fatty acids, vitamins, minerals, and plant extracts (Hoque *et al.*, 2022).

Globally, the nutraceutical market is experiencing exponential growth, particularly in the Asia-Pacific region, which holds a significant share of the market due to its large population base, rising disposable incomes, and increasing health consciousness (Fortune Business Insights, 2024). This growth is fueled by several converging global trends: an aging population seeking longevity, a general desire for 'clean-label' and natural products, and advancements in scientific research that provide evidence-based validation for specific health claims.

Crucially, this health-conscious movement is being redefined by the demographics of Generation Z (Gen Z) - individuals generally born between 1997 and 2012 (McKinsey, 2024). This generation, the first to be fully digital-native, views health holistically, integrating mental well-being, physical fitness, and diet. Unlike previous generations that relied heavily on traditional media and medical advice, Gen Z relies on digital platforms, social media, health and fitness apps, and online influencers as a primary source of health information (Ken Research, 2023). This reliance makes them highly susceptible to global trends in functional foods and supplements, but it also exposes them to considerable misinformation and 'fad' diets. The global trends, therefore, are characterized by a high degree of personalization and digital mediation in nutraceutical consumption, presenting both immense opportunities for targeted nutrition and significant challenges regarding informed decision-making and product efficacy. Understanding how Gen Z navigates this complex, digitally driven health landscape is essential to capturing the future direction of public health intervention (Jones, 2018).

The global paradigm shift towards preventing health has led to the exponential growth of the nutraceutical market, which is now heavily mediated by digital platforms and social media, particularly among Generation Z (Gen Z) (Fortune Business Insights, 2024). While nutraceuticals offer potential benefits, the digitally driven consumption exposes consumers to significant risks from misinformation and unregulated products.

Bangladesh is currently navigating a severe "nutrition transition", characterized by a "double burden of malnutrition" where micronutrient deficiencies coexist with rapidly rising rates of overweight and obesity, acutely impacting the youth population. In this vulnerable context, nutraceuticals are entering the urban mainstream, often promoted through direct-to-consumer digital marketing and unverified peer recommendations, rather than evidence-based medical necessity. The local market remains largely unregulated, compounding the risks of product authenticity and efficacy.

Despite the confluence of these critical factors-a vulnerable youth population (Gen Z) in a high-transition urban center (Khulna) engaging with an unregulated market via digital influence-there is a critical lack of empirical data regarding the actual engagement dynamics. Specifically, the problem lies in the unknown extent and nature of this interaction:

i. The knowledge gap: The actual nutritional literacy and perceptions of Gen Z in Khulna regarding the benefits and risks of nutraceuticals are undocumented, making it impossible to gauge their susceptibility to digital misinformation (Jones, 2018).
ii. The influence gap: The specific roles of digital influencers, social networks, and local market factors in driving consumption patterns remain unquantified and poorly understood.

iii. The regulatory gap: The challenges faced by consumers, such as affordability, product authenticity, and lack of professional guidance, have not been empirically analyzed within this specific local context.

Consequently, without a structured understanding of Gen Z's perceptions, usage patterns, and the critical factors influencing their choices in Khulna city, policymakers, public health educators, and regulatory bodies in Bangladesh are unable to develop effective, targeted public health interventions. This research is necessary to ground the national and global narrative in local evidence, thereby ensuring informed and safe nutritional decision-making for the nation's future demographic (Halicka *et al.*, 2025).

The general objective of this study is to empirically investigate the drivers, patterns, and challenges associated with nutraceutical consumption among Generation Z in Khulna city, Bangladesh, to inform targeted public health and regulatory policies.

i. To describe the socio-economic characteristics of the Generation Z respondents in Khulna city.
ii. To assess the perceived knowledge and awareness of nutraceuticals among the Generation Z respondents.
iii. To analyze the trends of nutraceutical usage (including types, frequency, and duration) among the Generation Z respondents.
iv. To identify the factors influencing the attitudes and behaviors toward nutraceutical use among the Generation Z respondents.
v. To determine the perceived problems and challenges faced by the Generation Z respondents in using nutraceutical products.

Bangladesh is facing a dual nutrition crisis, with both micronutrient deficiencies and rising obesity/NCDs. In this context, nutraceutical use is growing rapidly, often without evidence-based guidance. This study focuses on Generation Z, highly influenced by digital media, to examine their awareness, usage patterns, and vulnerabilities related to nutraceuticals. It also investigates how unregulated digital marketing and influencers shape their consumption. The research will generate the first empirical evidence from Khulna to support regulatory bodies in improving labeling, marketing standards, and public awareness campaigns. Overall, it aims to protect Gen Z from misinformation, ineffective or counterfeit products, and potential nutritional risks while strengthening national public health and nutrition security.

The research is limited to the Khulna City Corporation area and focuses solely on Generation Z (ages 12–27). It examines three core areas: (1) awareness and perceptions of nutraceuticals, (2) usage patterns, including types, frequency, and motivations, and (3) key influencing factors, especially digital media and social influence. The study includes various nutraceuticals such as supplements, functional foods, and fortified beverages, but excludes conventional pharmaceuticals and traditional herbal products not marketed through modern digital platforms.

The study has several limitations. Its non-probability sampling in a single urban area (Khulna) restricts generalizability. Self-reported data may suffer from recall and social desirability bias. Variations in how respondents interpret the term "nutraceuticals" may affect accuracy. The cross-sectional design allows only associations, not causal conclusions or trend analysis. Finally, relying on digital access may exclude less digitally connected Gen Z individuals, introducing selection bias.

## Methodology

This study employed a structured and replicable methodological approach to investigate nutraceutical awareness, perceptions, usage patterns, and influencing factors among Generation Z in Khulna, Bangladesh.

### *Locale of the study*

The research was conducted in the Khulna City Corporation area, a major urban and educational hub with a high concentration of Gen Z individuals. Data were collected from selected institutions, including Khulna University, Khulna City Corporation Women's College, Navy Anchorage School and College Khulna, and Islamabad Collegiate School and College Khulna. The city was chosen due to its socio-demographic diversity, accessibility, and increased youth exposure to health trends and nutraceutical products.

***Selection of respondents***

Respondents were Gen Z individuals aged 15–28 years (born 1997–2012) residing in Khulna. The sample included university and college students, employed youth, and self-employed individuals to capture diverse awareness and usage patterns. Both nutraceutical users and non-users were intentionally included. A non-probability purposive sampling technique was adopted to ensure the inclusion of individuals likely to have exposure to nutraceuticals. A total of 100 respondents were selected based on age, location, willingness to participate, and basic awareness of nutraceutical products. The number of respondents was selected purposively due to some unavoidable circumstances, such as time constraints and resource limitations. Since it was convenient and manageable for us to work with 100 respondents, that's why we have selected this sample size. Point to be noted that this sample size does not represent the entire Gen Z population of Bangladesh.

***Population and sampling procedure***

The target population comprised accessible Gen Z individuals living in Khulna city. Convenience sampling was used due to time and resource constraints, focusing on students and young adults in the community. Although this sampling method limits generalizability, it enabled efficient data collection across diverse socio-economic and educational backgrounds.

***Research instrument***

Data were collected using a structured questionnaire developed from existing literature. The instrument included sections on:

a) **Socio-demographic information** (age, gender, education, income, occupation).
b) **Awareness and knowledge** of nutraceuticals.
c) **Perceptions and attitudes**, measured with 5-point Likert scales.
d) **Usage patterns**, including type, frequency, duration and purpose of consumption.
e) **Influencing factors**, such as digital media, marketing, peer influence and affordability.

The questionnaire was prepared in English and verbally translated into Bangla for linguistic appropriateness. A back-translation process ensured meaning accuracy. Subject experts reviewed the draft to establish content validity. The questionnaire was translated into Bangla because of convenience for some respondents. A test study was conducted with the Bangla-translated questionnaire first on some respondents, which ensured the clarity of the translated terms.

***Data collection procedure***

Data were collected using both face-to-face interviews and self-administered surveys, depending on respondent convenience. Study objectives were explained, and informed consent was obtained. Clarifications were provided in Bangla when required. Each questionnaire required approximately 15–20 minutes. Completed questionnaires were checked immediately to minimize errors. Data collection occurred from 11 May to 13 June, 2025**.**

***Variables and measurement***

Variables were categorized into five groups:

a) **Socio-economic characteristics:** age, education, family type, income, occupation, organizational participation, and training. Measured using categorical and ordinal scales.
b) **Awareness and perceptions:** indicators: awareness level, source of knowledge, perceived benefits. Measured using awareness and perception indices (low, moderate, high).
c) **Usage trends:** indicators: types of products used, frequency, duration, purpose, expenditure, and brand preference. Measured using indices and categorical responses.
d) **Influencing factors:** digital media exposure, peer influence, and marketing. Measured using influence indices.
e) **Problems and challenges:** lack of knowledge, high cost, limited availability, authenticity concerns, side effects, and social/cultural barriers. Measured using 5-point Likert scales.

***Data processing, tabulation and analysis***

Data were processed and analyzed using SPSS. Qualitative responses were coded into numerical values. Indices and scales were constructed through score accumulation for efficient data reduction. Statistical tools used included frequency, percentage, mean, range, maximum, minimum, and standard deviation. A master sheet was prepared to tabulate all variables, enabling systematic interpretation aligned with study objectives.

## Results and Discussion

The findings of the present study are organized around five key objectives to provide a comprehensive understanding of Gen Z respondents' perceptions and problems regarding nutraceuticals in Khulna city. The results first describe the socio-economic characteristics of the respondents, offering a contextual background of the surveyed population. This is followed by an analysis of their perceptions and awareness of nutraceuticals, highlighting their level of knowledge and attitudes (Smith, 2020). Subsequently, the trends and influencing factors shaping the use of nutraceuticals among the respondents are discussed. Finally, the study addresses the perceived problems and challenges faced by Gen Z in adopting nutraceuticals. Together, these insights form the basis for understanding the current status and potential of nutraceutical awareness and usage in the study area.

### *A. Socio-economic characteristics of the respondents*

Table 1 presents an overall summary of the socio-economic characteristics of the respondents, covering key demographic and lifestyle variables such as age, education level, family size, land inheritance status and consumption of food from inherited lands. The Table also includes information on organizational participation, family monthly income, socialization habits, and training received on various topics, including food and nutraceutical products. Quantitative measurements are provided for each characteristic, showing the number and percentage of respondents in different categories, along with ranges, means, and standard deviations where applicable.

Table 1. Distribution of the respondents on the basis of socio-economic characteristics.

| Selected Characteristics (Measuring unit) | Categories | Scores | Number | Percent | Range (Min.-Max.) | Mean±SD |
|---|---|---|---|---|---|---|
| Age (Year) | Young | 15-28 | 100 | 100.0 | 15-28 | 21.95±2.96 |
| Education (Scores) | No<br>Primary<br>SSC<br>HSC<br>Honors<br>Above | 0<br>1-5<br>6-10<br>11-12<br>13-16<br>>16 | 0<br>0<br>11<br>16<br>70<br>3 | 0.0<br>0.0<br>11.0<br>16.0<br>70.0<br>3.0 | 8-17 | 13.67±2.33 |
| Family size (Number) | Small<br>Medium<br>Large | ≤4<br>5-6<br>>6 | 57<br>30<br>13 | 57.0<br>30.0<br>13.0 | 2-15 | 4.85±2.08 |
| Land Inheritance | Yes<br>No | 1<br>2 | 90<br>10 | 90.0<br>10.0 | - | 1.10±0.30 |
| Food from Inherited land | Yes<br>No | 1<br>2 | 54<br>46 | 54.0<br>46.0 | - | 1.46±0.50 |
| Name of foods (For Yes) | Grains<br>Fruits<br>Vegetables<br>Fish | 1<br>2<br>3<br>4 | 23<br>12<br>11<br>8 | 23.0<br>12.0<br>11.0<br>8.0 | - | 2.07±1.11 |
| Organizational Participation (Scores) | Low<br>Medium<br>High | ≤6<br>7-12<br>>12 | 100<br>0<br>0 | 100.0<br>0.0<br>0.0 | - | 1.88±0.32 |
| Family monthly Income (BDT) | Low<br>Medium<br>High | ≤30,000<br>30001-50,000<br>>50,000 | 13<br>32<br>55 | 13.0<br>32.0<br>55.0 | - | 2.42±0.71 |
| Socialization with family and friends and visits | Not at all<br>Rarely<br>Occasionally<br>Regularly | 0<br>1<br>2<br>3 | 0<br>8<br>19<br>73 | 0.0<br>8.0<br>19.0<br>73.0 | - | 2.65±0.62 |
| Training received | Yes<br>No | 1<br>2 | 5<br>95 | 5.0<br>95.0 | - | 1.95±0.21 |
| Training received on food | Yes<br>No | 1<br>2 | 3<br>97 | 3.0<br>97.0 | - | 1.97±0.17 |

The survey was conducted among 100 Gen Z individuals in Khulna city, aged between 15 and 28 years, with a mean age of 21.95 years. In terms of educational attainment, the majority of respondents (70%) were enrolled at the Honors level, while the remaining participants had completed their education at the SSC or HSC levels. Family size distribution indicated that most respondents (57%) belonged to small families comprising four or fewer members. In contrast, a smaller proportion came from medium-sized families, and only a few represented large families. A substantial majority (90%) reported having inherited land, with slightly more than half (54%) receiving food from these lands, primarily in the form of grains, fruits, vegetables, and fish.

Organizational participation was relatively low, with a mean value of 1.88, indicating limited involvement in such activities. The maximum positive score for organizational participation was only 12.0% out of 100 respondents. Because the Gen Z population spends more time on gadgets, they appear to be less interested in organizational participation. Family income levels were concentrated within the medium to high categories, with only a small percentage falling under the low-income group; the mean income score was 2.42. Socialization was reported by 73% of respondents, reflecting a relatively high level of interaction, largely attributed to their status as students regularly attending educational institutions. Participation in training programs was minimal, with a mean score of 1.95, and training specifically related to food and nutraceutical products was similarly limited, with a mean score of 1.97. Finally, regarding nutraceutical consumption, 43% of respondents reported using such products, while 57% did not, resulting in a mean score of 1.57.

As the data indicate, most Gen Z individuals are sufficiently well educated to understand health awareness issues related to nutraceuticals, suggesting that awareness of such products is relatively high among this group. The family size distribution reflects a modern socio-economic pattern, with smaller families being more common. Almost all respondents reported inheriting land, and a proportion of them also obtained food from these lands, which serves as an important source of natural nutrition through grains, fruits, vegetables, and fish. Organizational participation, however, was found to be consistently low among the respondents. Family monthly income was predominantly in the medium to high range, which aligns with the current upward economic trends. Socialization was reported to be regular, as participants, being students, frequently engage with peers and family members. Training opportunities, particularly on food-related subjects, were notably limited. Finally, nutraceutical consumption was relatively balanced, with 43% of respondents reporting use and 57% reporting non-use, indicating no substantial difference between consumers and non-consumers.

The findings from this survey are consistent with and can be contextualized within the existing literature on the health and dietary behaviors of Generation Z. Previous research highlights Gen Z as a health-conscious generation, with a strong emphasis on wellness and preventive health practices (McKinsey, 2024). Their relatively high levels of education may contribute to both their health awareness and their pursuit of reliable health information, including knowledge related to nutraceuticals. Other studies have shown that while Gen Z's food choices are primarily influenced by taste, price, and health considerations, social media and consumer trends also exert a noticeable, though secondary, influence (Halicka *et al.*, 2025). This may help explain the popularity of certain nutraceuticals, which are frequently marketed online.

A distinctive feature of this study is the data on land inheritance and access to food derived from such land. Although participants generally represent modern socio-economic conditions, many still retain access to traditional, natural food sources such as grains, fruits, vegetables and fish from inherited lands. This pattern aligns with broader consumer preferences documented in nutraceutical research, where there is an increasing shift toward natural-origin products and a gradual move away from synthetic alternatives (Hoque *et al.*, 2022). With regard to nutraceutical consumption, the findings reveal a relatively small difference between consumers (43%) and non-consumers (57%). This indicates that, overall, the socio-economic characteristics of the respondents align closely with those of contemporary urban society, with no substantial divergence in health-related behaviors between the two groups.

***B. Perceptions and awareness of the respondents***

Perceptions and awareness of the respondents regarding nutraceuticals were assessed through two key dimensions: perceived knowledge and perceived awareness. These indicators provide insights into how well Gen Z individuals in Khulna city understand nutraceutical products and the extent to which they are conscious of their potential health benefits. Together, these measures help capture both the cognitive and attitudinal aspects of respondents' orientation toward nutraceutical use.

Table 2 presents the results of the knowledge assessment, highlighting the distribution of knowledge categories among the 100 respondents. The Table provides quantitative measurements for each characteristic, including the number and percentage of participants across different categories, as well as ranges, means, and standard deviations where applicable. This section specifically examines the perceived knowledge and awareness of nutraceuticals among Gen Z respondents. The data illustrate the frequency and proportion of participants classified into four distinct knowledge levels: none, low, medium and high.

Table 2. Distribution of the respondents based on the perceived knowledge.

| Categories | Score | Respondents N=100 | | Mean±Standard Deviation | Range | |
|---|---|---|---|---|---|---|
| | | Frequency | Percent | 7.06 ± 2.09 | Min. | Max. |
| | | | | | 1 | 10 |
| None | 0 | 0 | 0.0 | | | |
| Low | ≤3 | 7 | 7.0 | | | |
| Medium | 4-6 | 28 | 28.0 | | | |
| High | >6 | 65 | 65.0 | | | |

The results indicate that a majority of respondents (65.0%) demonstrated a high level of knowledge, while (28.0%) exhibited a medium level of knowledge. Only a small proportion (7.0%) reported a low level of knowledge, and no respondents were found to have a score of zero, suggesting that all participants possessed at least some degree of knowledge. The overall mean score was 7.06 ± 2.09, with observed scores ranging from 1 to 10.

The survey suggests that the group holds a comprehensive knowledge base. A large proportion of respondents achieving a high knowledge is an important observation, as it reflects either successful knowledge dissemination or a well-informed group. The mean score of 7.06 with a standard deviation of 2.09 indicates that most scores are concentrated near the average.

Table 3. Distribution of the respondents based on the perceived awareness.

| Categories | Score | Respondents N=100 | | Mean±Standard Deviation | Range | |
|---|---|---|---|---|---|---|
| | | Frequency | Percent | 44.77 ± 9.30 | Min. | Max. |
| | | | | | 22 | 60 |
| None | 0 | 0 | 0.0 | | | |
| Low | ≤35 | 19 | 19.0 | | | |
| Medium | 36-55 | 61 | 61.0 | | | |
| High | >55 | 20 | 20.0 | | | |

Table 3, titled "Perceived Awareness," presents the distribution of awareness levels among 100 respondents. Participants were categorized into different levels of awareness based on their scores. The majority of respondents (61.0%) demonstrated a medium level of awareness, while 19.0% and 20.0% reported low and high levels of awareness, respectively. Notably, no respondents scored zero, indicating that all participants possessed at least some awareness of nutraceutical products. The overall mean score was 44.77 ± 9.30, with a range of 22 to 60. These results suggest that awareness among Gen Z respondents is generally moderate, neither very low nor exceptionally high, yet the absence of a zero score reflects a baseline level of awareness across the entire group.

The data indicate that the 100 respondents exhibit a moderate level of awareness, with the majority falling into the medium category. In contrast to the knowledge assessment, where a substantial proportion of participants demonstrated high knowledge, the awareness results reveal a more balanced distribution, with most respondents clustered around the medium level. The mean score of 44.77, with a standard deviation of 9.30, suggests that awareness levels are generally consistent across the group. This balanced distribution implies that respondents possess a reasonable degree of awareness and are likely to exercise caution in their consumption of nutraceutical products.

The findings from the awareness assessment reveal a distinct pattern compared to the perceived knowledge results. While the knowledge data indicated that respondents are generally well-informed, with a high proportion falling into the high knowledge category, the awareness results suggest a more moderate level of understanding. This discrepancy highlights a potential distinction between perceived knowledge, what participants know, and perceived awareness, their conscious recognition and comprehension of the topic.

### *C. Trends and Influencing factors among the respondents*

Trends and influencing factors among the respondents were examined through five key dimensions: perceived benefits, motivation and the role of digital media, peer influence and marketing. These indicators provide insights into the factors shaping Gen Z's attitudes and behaviors toward nutraceutical products. By analyzing these aspects, the study aims to identify the drivers behind consumption patterns and the social, technological, and promotional elements that influence their choices.

The following Tables present the trends and factors influencing the respondents' attitudes and behaviors toward nutraceutical products. Table 4 illustrates perceived benefits, categorizing respondents into "None," "Low," "Medium," and "High" levels, along with their corresponding frequencies and percentages. Table 5 summarizes respondents' motivations, similarly classified across four levels with respective frequencies and percentages. Table 6 highlights the role of digital media, showing the extent of its influence on respondents, while Table 7 details peer influence across the same categorical levels. Finally, Table 8 presents the role of marketing, indicating the distribution of respondents according to "None," "Low," "Medium" and "High" levels of marketing influence. Together, these Tables provide a comprehensive overview of the key drivers shaping Gen Z's engagement with nutraceutical products.

Table 4. Distribution of the respondents based on the perceived benefits.

| Categories | Score | Respondents N=100 | | Mean±Standard Deviation | Range | |
|---|---|---|---|---|---|---|
| | | Frequency | Percent | 32.23 ± 7.38 | Min. | Max. |
| | | | | | 15 | 44 |
| None | 0 | 0 | 0.0 | | | |
| Low | ≤13 | 0 | 0.0 | | | |
| Medium | 14-30 | 34 | 34.0 | | | |
| High | >30 | 66 | 66.0 | | | |

In the Table, we can see that the High perceived benefits: 66 out of 100 respondents (66.0%). Medium perceived benefits: 34 out of 100 respondents (34.0%). Low or no perceived benefits: 0 out of 100 respondents (0.0%). The mean score is 32.23 ± 7.38, with a range of 15 to 44.

The data suggest that the vast majority of the respondents have a positive perception of the benefits associated with the subject of the study. The high percentage of respondents in the "High" category (66.0%) indicates that the benefits are widely and strongly perceived. The absence of respondents in the "Low" and "None" categories further reinforces that the perceived benefits are universally recognized among the participants.

This finding highlights the significant role that perceived benefits play in the context of the study. A strong perception of benefits is a powerful driver for behavior and engagement. The high mean score and the

absence of low or no-benefit perceptions suggest that the benefits are either very clear, tangible, or well-communicated to the population studied. This could be due to effective marketing, strong peer-to-peer recommendations, or the inherent value of the product or service itself. Future research could explore which specific benefits are most valued by the "High" category respondents.

Table 5. Distribution of the respondents based on the motivation.

| Categories | Score | Respondents N=100 | | Mean±Standard Deviation | Range | |
|---|---|---|---|---|---|---|
| | | Frequency | Percent | 15.14 ± 3.27 | Min. | Max. |
| | | | | | 7 | 21 |
| None | 0 | 0 | 0.0 | | | |
| Low | ≤9 | 7 | 7.0 | | | |
| Medium | 10-18 | 67 | 67.0 | | | |
| High | >18 | 26 | 26.0 | | | |

In the Table for motivation, it is depicted that Medium motivation: 67 out of 100 respondents (67.0%). High motivation: 26 out of 100 respondents (26.0%). Low motivation: 7 out of 100 respondents (7.0%). No motivation: 0 out of 100 respondents (0.0%). The mean score is 15.14 ± 3.27, with a range of 7 to 21.

The results indicate that most respondents have a medium level of motivation (67.0%). A notable portion also falls into the high motivation category (26.0%). The remaining (7.0%) have low motivation, and no respondents have no motivation at all. This suggests a generally positive but not overwhelmingly high level of motivation among the group.

While a majority of respondents are moderately motivated, the data also reveals a significant group with high motivation and a small group with low motivation. The results suggest that motivation is a key factor, but it's not uniformly high across the population. The moderate level of motivation could be influenced by various factors. Understanding what differentiates the highly motivated group from the moderately or lowly motivated groups would be valuable. The study should further explore the specific drivers behind these different levels of motivation, such as personal goals, external rewards, or internal satisfaction.

Table 6. Distribution of the respondents based on the role of digital media.

| Categories | Score | Respondents N=100 | | Mean±Standard Deviation | Range | |
|---|---|---|---|---|---|---|
| | | Frequency | Percent | 15.11 ± 3.21 | Min. | Max. |
| | | | | | 6 | 22 |
| None | 0 | 0 | 0.0 | | | |
| Low | ≤9 | 5 | 5.0 | | | |
| Medium | 10-18 | 73 | 73.0 | | | |
| High | >18 | 22 | 22.0 | | | |

Role of digital media influences, medium role of digital media: 73 out of 100 respondents (73.0%). High role of digital media: 22 out of 100 respondents (22.0%). Low role of digital media: 5 out of 100 respondents (5.0%). No role of digital media: 0 out of 100 respondents (0.0%). The mean score is 15.11 ± 3.21, with a range of 6 to 22.

A significant majority of respondents (73.0%) report that digital media plays a medium role. 22.0% of respondents feel it plays a high role, and a small minority (5.0%) feel it plays a low role. No respondents felt that digital media played no role. This highlights the considerable but not universally dominant influence of digital media on the respondents.

The findings confirm the widespread influence of digital media, with almost all respondents acknowledging its role to some extent. The large percentage in the medium category suggests that while digital media is an influential factor, it may not be the sole or primary driver for the majority. This implies that digital media serves as a consistent, supporting influence rather than a powerful, deciding factor. Further investigation could explore the specific platforms (e.g., social media, news sites, etc.) and types of content that contribute most to this influence.

Table 7. Distribution of the respondents based on the role of peer influence.

| Categories | Score | Respondents N=100 | | Mean±Standard Deviation | Range | |
|---|---|---|---|---|---|---|
| | | Frequency | Percent | 15.40 ± 4.55 | Min. | Max. |
| | | | | | 2 | 25 |
| None | 0 | 0 | 0.0 | | | |
| Low | ≤9 | 8 | 8.0 | | | |
| Medium | 10-18 | 66 | 66.0 | | | |
| High | >18 | 26 | 26.0 | | | |

In the Table for peer influence, medium peer influence: 66 out of 100 respondents (66.0%). High peer influence: 26 out of 100 respondents (26.0%). Low peer influence: 8 out of 100 respondents (8.0%). No peer influence: 0 out of 100 respondents (0.0%). The mean score is 15.40 ± 4.55, with a range of 2 to 25.

The data reveal that peer influence has a medium role for the majority of respondents (66.0%). A smaller but substantial group (26.0%) reports a high level of peer influence, and 8.0% report a low level. No respondents were unaffected by peer influence. This demonstrates that social circles and peer opinions are a significant factor for the respondents.

The results are consistent with the general understanding of social dynamics, where peer influence plays a considerable role in shaping opinions and behaviors. The fact that a large majority fall into the medium and high influence categories suggests that social validation and peer opinions are important factors for the respondents. This could have significant implications for strategies that leverage word-of-mouth or community building.

Understanding what specific peer behaviors, opinions, or recommendations are most influential would be a valuable next step.

Table 8. Distribution of the respondents based on the role of marketing.

| Categories | Score | Respondents N=100 | | Mean±Standard Deviation | Range | |
|---|---|---|---|---|---|---|
| | | Frequency | Percent | 18.07 ± 4.27 | Min. | Max. |
| | | | | | 5 | 24 |
| None | 0 | 0 | 0.0 | | | |
| Low | ≤9 | 4 | 4.0 | | | |
| Medium | 10-18 | 38 | 38.0 | | | |
| High | >18 | 58 | 58.0 | | | |

The role of marketing in this sector is: High role of marketing: 58 out of 100 respondents (58.0%). Medium role of marketing: 38 out of 100 respondents (38.0%). Low role of marketing: 4 out of 100 respondents (4.0%). No role of marketing: 0 out of 100 respondents (0.0%). The mean score is 18.07 ± 4.27, with a range of 5 to 24.

The findings indicate that for the majority of respondents (58.0%), marketing plays a high role. A large portion (38.0%) feels that marketing plays a medium role, with only a small minority (4.0%) reporting a low role. No respondents reported a role for marketing. This suggests that marketing is a very powerful and influential factor for the population under study.

The data confirms the significant impact of marketing strategies, as evidenced by the high percentage of respondents who report its strong influence. The fact that a combined (96.0%) of respondents fall into the medium or high categories suggests that marketing efforts are effectively reaching and influencing the target audience. This indicates that well-executed marketing campaigns are likely to be a primary driver of success in this context. Further research could delve into which specific marketing channels, messages, or campaigns resonate most effectively with the audience.

### *D. Perceived problems of the respondents*

Table 9 presents perceived problems related to nutraceutical products; it includes data from a survey of 100 participants. The Table lists 15 potential problems, each with a corresponding problem score, problem index %, and rank. Participants rated each problem on a severity scale from 0 to 3. (Not at all 0), (Less Severe 1), (Moderately Severe 2), and (Highly Severe 3). The scores are calculated by multiplying the rating value by

the number of people who chose that rating for each problem. The problem score for each issue is the sum of these calculated values. The problem index is then calculated by dividing the problem score by the maximum possible score of 300 and multiplying by 100. The most perceived problem from this Table has been found to be that the price of most nutraceutical products is very high and sometimes out of reach of most customers. This ranked in the 1st position. The 2nd problem is the uncertainty of the usage and dosage of the nutraceutical products for consumption. The 3rd problem is that there is a lack of clear conception and knowledge about nutraceutical products. These three problems are the most ranked problems that have been perceived from the respondents.

Table 9. Distribution of the respondents based on the perceived problems.

| No. | Perceived Problem | Not at all (0) | Less Severe (1) | Moderately Severe (2) | Highly Severe (3) | Problem Score | Problem Index (%) | Rank |
|---|---|---|---|---|---|---|---|---|
| 1. | High cost of nutraceutical products | 0×0 | 1×8 | 2×18 | 3×74 | 266 | 88.66 | 1st |
| 2. | Lack of clear information about benefits and side effects | 0×4 | 1×9 | 2×19 | 3×68 | 251 | 83.66 | 3rd |
| 3. | Confusion due to too many product choices | 0×16 | 1×30 | 2×42 | 3×12 | 150 | 50.00 | 14th |
| 4. | Difficulty in distinguishing genuine products from fake or low-quality ones | 0×8 | 1×8 | 2×24 | 3×60 | 236 | 78.66 | 6th |
| 5. | Limited availability of trusted brands in local markets | 0×1 | 1×21 | 2×56 | 3×22 | 199 | 66.33 | 10th |
| 6. | Fear of side effects or adverse reactions | 0×1 | 1×14 | 2×18 | 3×67 | 252 | 83.67 | 4th |
| 7. | Lack of trust in product claims and advertisements | 0×3 | 1×22 | 2×46 | 3×29 | 201 | 67.00 | 9th |
| 8. | Uncertainty about proper dosage and usage instructions | 0×3 | 1×4 | 2×27 | 3×66 | 256 | 85.33 | 2nd |
| 9. | Limited consultation or guidance from healthcare professionals | 0×3 | 1×11 | 2×28 | 3×58 | 241 | 80.33 | 5th |
| 10. | Social stigma or negative perception about using supplements | 0×25 | 1×33 | 2×27 | 3×15 | 132 | 44.00 | 15th |
| 11. | Misleading information from social media or unverified sources | 0×6 | 1×29 | 2×35 | 3×30 | 189 | 63.00 | 12th |
| 12. | Difficulties in accessing reliable online purchasing platforms | 0×2 | 1×16 | 2×54 | 3×28 | 208 | 69.33 | 8th |
| 13. | Lack of awareness about possible interactions with medicines | 0×4 | 1×12 | 2×28 | 3×56 | 237 | 78.67 | 7th |
| 14. | Perceived ineffectiveness or slow results after using the product | 0×7 | 1×37 | 2×39 | 3×17 | 166 | 55.33 | 13th |
| 15. | Regulatory concerns-uncertainty if products are approved and safe | 0×4 | 1×23 | 2×51 | 3×22 | 191 | 63.66 | 11th |

Based on the survey of 100 participants, the most significant problems associated with nutraceutical products were identified and ranked according to their problem indices. The primary concern was the high cost of nutraceutical products, which received a problem index of 88.66% and a score of 266. The second most prominent issue was uncertainty regarding proper dosage and usage instructions, with a problem index of 85.33% and a score of 256. The third-ranked problem was the lack of clear information about benefits and side effects, with a problem index of 83.66% and a score of 251. The fourth-ranked issue was the fear of potential adverse reactions, with a problem index of 83.67% and a score of 252. These findings highlight the key barriers faced by Gen Z respondents in effectively using nutraceutical products.

The least significant problems identified by the respondents included social stigma or negative perceptions about using supplements, which ranked 15th with a problem index of 44% and a score of 132. Confusion arising from the availability of too many product choices was ranked 14th, with a problem index of 50% and a score of 150. Perceived ineffectiveness or slow results after using nutraceutical products ranked 13th, with a problem index of 55.33% and a score of 166. These findings suggest that, while present, these issues are relatively less critical compared to other challenges faced by Gen Z consumers.

The results show that consumers are primarily concerned with issues related to product information, safety, and cost. The top-ranked problem, high cost, is a significant financial barrier for consumers. This suggests that despite a willingness to use these products, the price point is a major deterrent. The high rankings of "uncertainty about proper dosage," "lack of clear information," and "fear of side effects" all point to a critical need for better consumer education and transparency from manufacturers and healthcare providers. Consumers appear to be hesitant due to a lack of trustworthy, accessible information, which can lead to a perception of risk. The problem of "limited consultation or guidance from healthcare professionals" further reinforces this, indicating a gap in professional support and advice for consumers. The lower-ranked problems, such as "social stigma" and "confusion due to too many product choices," suggest that these are less pressing issues for the surveyed group. This indicates that the direct, practical concerns of cost and safety are far more impactful than social or market-related issues.

The findings indicate a strong correlation between consumer trust and the reported problems. The most severe problems identified are those that directly impact a consumer's ability to make an informed, safe, and cost-effective decision. The highest-ranking problem, the high cost of nutraceuticals, is a straightforward economic barrier, but the subsequent problems are more complex, stemming from an information deficit. The data suggests that simply having products available isn't enough; consumers require accessible, reliable information to feel confident in their purchase and usage. The fact that problems like "lack of awareness about possible interactions with medicines" and "difficulty in distinguishing genuine products from fake" are also highly ranked underscores the public health implications of this information gap. To address these concerns, stakeholders in the nutraceutical industry, including manufacturers, regulators and healthcare professionals, should prioritize initiatives that improve product labeling, public education campaigns and professional guidance. By doing so, they can build consumer trust, enhance product safety, and ultimately increase the responsible use of nutraceuticals.

## Discussion

The purpose of this chapter is to give a review of the literature that is relevant to the current study. This study was carried out to investigate the nutraceutical awareness and usage among Gen Z in Khulna. The researcher made an exhaustive search of available literature to find out studies dealing with nutraceutical awareness and usage. During the review, the researcher discovered studies examining the relationship between the rise of nutraceutical imperative, the dominant economic barrier, prioritization of practical concerns, and the characteristics, namely age, education, family size, family income, training, knowledge on nutraceuticals, organizational participation, influencing factors, and media contact directly or indirectly.

"Tendencies and attitudes towards dietary supplements use among undergraduate female students in Bangladesh" (Chowdhury *et al.*, 2021). This research specifically investigates the tendencies and attitudes

towards dietary supplement use among undergraduate female students (primarily the Gen Z age group) in Chittagong, Bangladesh. It covers prevalence, reasons for use (general health, physician recommendation, etc.), and their positive opinions/attitudes, which directly relate to our awareness, usage, and perception variables.

"Factors affecting consumers' decisions on the use of nutraceuticals: a systematic review" (Teoh *et al.*, 2019). This provides a comprehensive overview of motivating factors (perceived health benefits, safety, and advice from healthcare professionals/family) and barriers (lack of belief, high cost, lack of knowledge) to nutraceutical use globally. This will be an excellent resource for structuring our Influencing Factors and Problems sections.

"Exploring the factors affecting consumer behavior towards the purchase of Nutraceuticals in Pakistan" (Abid *et al.*, 2022). This directly investigates factors affecting consumer behavior for nutraceuticals among young consumers, finding that perceptions of health benefits, safety features, and the source of information are significant influencing factors. This directly mirrors our "Perceptions" and "Influencing Factors" variables.

"Food Choices of Gen Z University Students in Bangladesh" (Hossain *et al.*, 2024). This qualitative study explores factors driving food preferences among Gen Z university students in Bangladesh, including the role of social, technological, and cultural dynamics. While broader than nutraceuticals, it provides crucial context on health issues, nutrition levels, cost, and social media influence on Gen Z's food choices, all of which are relevant to nutraceutical usage.

***Introduction and the Gen Z consumer landscape***

The global health and wellness trend has driven the significant expansion of the nutraceutical market, which integrates nutrition and pharmaceuticals to offer disease-preventive and health-promoting products (Teoh *et al.*, 2019). This review focuses on Generation Z (Gen Z), a digitally native, health-conscious cohort that is highly influential in the market (Hossain *et al.*, 2024). While Gen Z expresses a strong inclination toward health, their urban, high-paced lifestyle often involves high consumption of accessible, inexpensive ultra-processed foods, creating a nutritional paradox that makes them relevant consumers for supplementary products (Hossain *et al.*, 2024). The diet of the Gen Z population is mostly composed of ultra-processed foods, so they tend to prefer products that are labeled as natural or of organic origin. Most of them have the misconception that nutraceuticals can fix their poor diets, which is not appropriate. They mainly think of nutraceutical supplements as a quick fix for their health, without maintaining a proper diet.

***Trends and prevalence of nutraceutical usage***

Research consistently demonstrates a high and rising prevalence of dietary supplement and nutraceutical consumption among young adults, forming a critical user segment. Studies conducted in the South Asian region, particularly in Bangladesh, show a highly prevalent use of dietary supplements among undergraduate students, a group largely composed of Gen Z (Chowdhury *et al.*, 2021). These consumers generally exhibit positive attitudes towards dietary supplements, primarily using them for general health and well-being, nutritional supplementation, immune support, and energy (Chowdhury *et al.*, 2021). However, a significant trend identified in the region is the widespread practice of self-medication. A large percentage of users initiate supplement intake and continue usage without consulting a healthcare professional like a physician or pharmacist, raising concerns about potential adverse effects and unverified claims (Chowdhury *et al.*, 2021). The global demand for nutraceuticals has been significantly boosted by consumer emphasis on disease prevention and a preference for natural, functional ingredients over synthetic drugs (Teoh *et al.*, 2019). The market's growth is further fueled by the desire for personalized nutrition and the heightened awareness of immune health following global events (Teoh *et al.*, 2019).

***Perceptions and key influencing factors***

Consumer behavior concerning nutraceuticals is heavily influenced by personal perceptions and external cognitive factors. Consumer attitudes and knowledge are consistently cited as strong, positive predictors of healthy and sustainable consumption behavior (Gan *et al.*, 2016). Specifically, the decision to purchase nutraceuticals is profoundly influenced by

the consumer's perception of the product's health benefits and its safety features (Abid *et al.*, 2022). Consumers, when evaluating purchase intent, often consider factors like taste and packaging, along with the core perceived benefits (Teoh *et al.*, 2019). Furthermore, an active lifestyle often correlates positively with the consumption of dietary supplements, suggesting that usage is integrated into a broader health-conscious routine (Gan *et al.*, 2016). The source of information is a statistically significant factor determining a consumer's decision to use nutraceuticals (Abid *et al.*, 2022). For Gen Z, the digital environment is the primary domain for information gathering. This dependence on online sources, including social media, makes the consumer susceptible to popular trends and influencer marketing. Trust in the information source and the product is also an integral component that dictates purchase intention (Gan *et al.*, 2016).

***Problems and barriers to informed usage***

Despite the high awareness, several problems, both cognitive and structural, act as barriers to the safe, effective, and equitable use of nutraceuticals. A key problem is the vulnerability of Gen Z to misinformation, pseudoscience, and exaggerated claims disseminated through digital media and online platforms (Hossain *et al.*, 2024). This challenge is amplified by issues of low nutritional literacy, making it difficult for consumers to differentiate between credible, evidence-based nutrition advice and viral, unverified trends (Chowdhury *et al.*, 2021). Structurally, the lack of stringent regulatory oversight for nutraceuticals, when compared to pharmaceuticals, allows manufacturers to make claims without robust clinical evidence (Teoh *et al.*, 2019). This regulatory gap increases safety concerns and contributes to consumer skepticism (Teoh *et al.*, 2019). The high cost of nutraceutical products is a frequently cited barrier for price-sensitive young adults, particularly in developing economies. This cost disparity often forces consumers to prioritize cheaper, readily available ultra-processed options over expensive nutraceuticals and fresh, nutrient-dense foods (Teoh *et al.*, 2019; Hossain *et al.*, 2024).

The current body of literature provides a strong framework detailing that Gen Z's nutraceutical usage is substantial, driven by positive health perceptions and digital influences, but constrained by misinformation, self-medication, and economic barriers. However, a critical research gap exists concerning the integrated study of all these variables: awareness, usage, perceptions, trends, factors, and problems within a specific, localized context. While regional data exists for large metropolitan centers, a comprehensive study focused solely on Gen Z in Khulna remains absent.

## Conclusion

This study demonstrates that although nutraceuticals hold substantial promise within the broader shift toward preventive healthcare, their responsible use is currently impeded by two interconnected challenges: economic inaccessibility and a pervasive information and trust deficit. This study identifies the high cost of these products as the primary barrier to adoption, yielding a dominant problem Index of 88.66%. This shows that despite a strong baseline of health consciousness among Gen Z in Khulna, the price point remains the critical factor restricting equitable access. High product costs restrict equitable access, while widespread concerns about safety, authenticity, and potential interactions with medications reveal a deeper structural issue tied to weak regulatory oversight and inconsistent information. The findings show that consumers are navigating a knowledge vacuum in which unclear labeling, limited professional guidance, and insufficient regulatory enforcement heighten public health risks. The long-term sustainability of the nutraceutical sector therefore requires a transition from a predominantly market-driven model to one grounded in consumer protection, ethical practice and scientific transparency. Restoring public confidence will depend on coordinated action across industry, regulatory authorities and healthcare professionals to create an environment where informed, safe and evidence-based decision-making becomes the norm.

## Recommendations

To address the identified trust and information gaps, a multi-level intervention framework is essential. First, manufacturers, under strengthened regulatory oversight, should implement standardized and mandatory labeling protocols that ensure clarity on potential drug–nutraceutical interactions, product authentication, and the scientific basis of health claims. Technologies such as QR

codes or blockchain should be mandated to enhance traceability and combat counterfeit products. There is currently no digital framework in Bangladesh where a QR code or blockchain is printed on supplement packaging. However, if this initiative is implemented by the Directorate General of Drug Administration (DGDA), it would make consumers' lives hassle-free regarding this issue. Providing accurate information about a supplement's brand, origin, dosage, usage, and other essential details through a QR code or blockchain that can be scanned by smartphones makes it easier to purchase and consume safely. Second, public health agencies and professional organizations must lead sustained educational initiatives that raise awareness of high-risk practices, particularly the concurrent use of supplements with chronic disease medications. The benefits of the product and the proper dosage should be clearly labeled on the packaging. Proper information about the product itself, including its dosage and usage, should be clearly communicated, either on the packaging, by a healthcare professional, or by the pharmacist. Developing centralized, unbiased digital repositories of nutraceutical information and leveraging pharmacies as frontline sources of guidance will further enhance consumer literacy. Finally, integrating healthcare professionals more directly into the nutraceutical information ecosystem is crucial. This includes revising medical and pharmacy curricula to incorporate evidence-based nutraceutical education, establishing clinical decision support tools for real-time interaction alerts, and creating professional certification systems to endorse products that meet rigorous safety and quality standards. Collectively, these measures will strengthen consumer protection, enhance transparency, and promote the safe and informed use of nutraceuticals in Bangladesh.

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# The growth, carcass yield traits, viability, meat quality and internal organ development of broiler fed betaine-supplemented diet

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**A B S T R A C T**

The study was undertaken to appraise the productive performance of broilers raised on a betaine-fed ration. A number of broilers (Cobb500, n=280) were taken as research materials and distributed randomly into 4 treatments in a CRD. $D_0$ (Control), $D_1$ (0.15 % betaine), $D_2$ (0.20 % betaine), and $D_3$ (0.25% betaine) were considered as treatments. Ten birds were assigned per replication, with seven replications per treatment. A battery cage was used to rear the chicks from d1-33. Starter diet was used from d1-14, then formulated diets were fed to the chicks from d15-33. Similar energy content and protein (%) were used for all the formulated diets. The results showed that feed intake, live weight, and feed conversion ratio were affected ($P<0.05$) by treatment. The live weight of the birds fed the $D_3$ diet was heavier ($P<0.05$) in the birds fed the $D_3$ diet than that of the other treatments. There was no difference ($P>0.05$) found in the survivability and intestinal organ weights. Meat yield traits were insignificant ($P>0.05$) except for dressing % and thigh weight. Broilers fed the $D_3$ diet had a greater ($P<0.05$) dressing % and thigh weight % than those of other groups. It can be concluded that better growth performance and higher profit can be obtained by rearing broilers with a betaine-supplemented diet.

**Keywords:** Growth, Carcass trait, Visceral organ, Survivability, Betaine, Broiler chicken

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## Introduction

Feeding an increasing number of people is becoming problematic day by day across the globe, because it is projected that by 2050 the intake of livestock products, poultry, dairy, and fish products will be doubled (Al-Dawood, 2015). A more efficient, sustainable, and cost-effective solution to these rising problems is to feed the animals properly to enhance their productivity to some extent. Broiler chicken is growing faster and more profitable all over the world. The salient point of poultry integrators is to attain the best productive performance by investing low capital/money in the poultry enterprise. This tendency of poultry farmers always pushes poultry integrators to find cheaper strategies for viable and lucrative poultry production.

However, poultry researchers are searching for different ways to promote poultry productivity, due to restrictions on animal by-products and the free use of antibiotics in livestock production by the E.U. (Adil *et al.*, 2010). Using natural plant extract betaine in poultry diets as feed additives for promoting poultry production can be a means of a sustainable solution. Nowadays, emphasis is being given to the use of natural plant extracts in animal science. Improving broiler productivity is still a major issue in the micro-livestock sector, particularly under adverse climatic or environmental conditions. The use or utilization of numerous supplements in poultry has been tried for a long time to explore the best production potentialities (Michiels *et al.*, 2012; Carvalho *et al.*, 2013).

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Betaine, as a derivative of micronutrients (amino acids) in nature, is commonly available (Liu *et al.*, 2019). Natural betaine is usually obtained from beet root (Botch *et al.*, 1997). It is considered a valuable common supplement that affects animal performance (Dunshea *et al.*, 2019). Now, this betaine, in synthetic form or as natural feed additives, is commonly available to prepare livestock or poultry rations. It is seen that betaine can serve numerous functions in the body, such as fat metabolism, an anti-heat stress agent, an osmo-protectant, and helps in various physiological systems (nervous, renal) (Eklund *et al.*, 2005; Hamidi *et al.*, 2010; Alirezaei *et al.*, 2012; Sakomura *et al*, 2013). The body weight gain or growth under stress conditions and feed utilization ability of poultry (broilers and ducks) are found to be improved when betaine is used as a feed supplement in the poultry diet (Zhan *et al.*, 2006; Attia *et al.*, 2009b; Rao *et al.*, 2011; Akhavan-Salamat and Ghasemi, 2016).

Animals have to face a lot of challenges or environmental stressors every day, which could affect broiler performance adversely. In this view, nutritional intervention or supplementation of various feed additives in the diet could be an appropriate means to reduce severe negative effects of climate on broilers (Attia *et al.*, 2009a; Silanikove and Koluman, 2015; Cheng *et al.*, 2018). Owing to the continuous changes in the climate scenario, the negative impact of heat stress derived from high environmental temperature on poultry production has now become an emerging issue around the globe, particularly in tropical climatic conditions (Virden and Kidd, 2009; Nawab *et al.*, 2018). The data on betaine application in broiler diets are scarce, and inconclusive results of previous works have warranted further study. Under the above circumstances, the current study was adopted to ascertain the growth performances, viability, carcass traits, meat quality, and gastrointestinal organ growth of broilers fed a betaine-included ration.

## Materials and Methods

The experimental animal shed of CVASU was used to conduct the feeding trial following the standard procedures as guided by CVASU, Chittagong. A total of 280 (Cobb500, 45±0.45g) broiler chicks were collected from a reputed poultry farm. The collected chicks' weight was recorded first. The chicks were assigned randomly into four treatments with 7 replicates, and ten birds were allotted in each replication in a completely randomized block design (CRD) in cages from d1 to 33 days. An electric bulb hanging at the top of each replicate cage or pen was used to brood the chicks at a temperature of 33°C for the first two days. After that, heat was decreased by 5°C every week until 19 days old, then 24°C temperature was maintained until the last day of the trial. Plastic feeders and plastic drinkers were given to each pen to facilitate the feeding and watering of birds. The lighting program for the chicks was continuous lighting (23h:1). Medication and vaccination were used to increase the immunization of the birds. Two vaccines, BCRDV and IB, were applied for the prevention of Ranikhet and Gumboro diseases. Besides, some saline solution along with a vitamin supplement was also used for the birds to reduce the risk of heat stress.

### *Diet formulation*

Locally available feedstuffs were used to formulate four different diets ($D_0$, $D_1$, $D_2$ and $D_3$). All prepared feeds had similar energy and protein (%) content. Basal or control feed ($D_0$) was formulated with betaine. In contrast, test diets ($D_1$, $D_2$ and $D_3$) were made by including the additive betaine (Betafin®, 96% Natural Betaine, Biochem Co., Brinkstrasse 55, D-49393 Lohne, Germany) at the rate of 0.15%, 0.20 %, and 0.25%, respectively (Table 2). Compound feed, i.e., starter ration (Nourish™), was purchased from the market, and this diet was used for 14 days (Table 1). Later, the test ration was fed to the broiler chicks from 15 to 33 days (Table 2). Broilers had access to feed and clean drinking water *ad libitum*. Prepared diets were also included with the multi-enzyme (Natuzyme). The nutritive values (analyzed in the lab) of the compound or ready feed starter and prepared diets (Tables 1 and 2).

Table 1. Nutrient composition of ready-made starter diet.

| Nutrient contents (%) | Proximate values of ready-made | Reporting values of ready-made |
|---|---|---|
| ME (kcal/kg) | 3356.68 | 2950 |
| Moisture | 9.95 | 9.98 |
| DM | 90.05 | 90.02 |
| CP | 21.20 | 21.00 |
| CF | 4.77 | 5.00 |
| EE | 6.98 | 5.00 |
| Ash | 5.23 | 6.00 |
| Ca | 1.00 | 1.00 |
| Total P | 0.58 | 0.45 |
| Lys | - | 1.30 |
| Met | - | 0.55 |

Table 2. Nutrient and ingredient composition of finisher diet.

| Ingredient (%) | Treatment | | | |
|---|---|---|---|---|
| | $D_0$ | $D_1$ | $D_2$ | $D_3$ |
| Maize | 58.00 | 58.00 | 58.20 | 58.12 |
| Wheat | 3.00 | 2.54 | 2.30 | 2.10 |
| Soybean meal | 30.00 | 30.00 | 29.30 | 29.30 |
| Protein concentrate | 2.34 | 2.36 | 3.00 | 3.00 |
| Palm oil | 3.70 | 3.87 | 3.80 | 3.89 |
| DCP | 0.40 | 0.37 | 0.34 | 0.34 |
| Limestone | 1.50 | 1.60 | 1.80 | 1.89 |
| Table salt | 0.25 | 0.30 | 0.25 | 0.30 |
| Choline chloride | 0.04 | 0.04 | 0.04 | 0.04 |
| Vitamin-mineral-premix | 0.25 | 0.25 | 0.25 | 0.25 |
| L-lysine | 0.18 | 0.18 | 0.18 | 0.18 |
| DL-methionine | 0.25 | 0.25 | 0.25 | 0.25 |
| Betafin | 0.00 | 0.15 | 0.20 | 0.25 |
| Enzymes (Natozyme) | 0.04 | 0.04 | 0.04 | 0.04 |
| Toxin binder | 0.05 | 0.05 | 0.05 | 0.05 |
| Nutrients (%)-calculated value | | | | |
| ME(Kcal/kg) | 3118 | 3119 | 3120 | 3119 |
| CP | 20.54 | 20.51 | 20.57 | 20.54 |
| CF | 3.43 | 3.42 | 3.40 | 3.39 |
| EE | 3.49 | 3.48 | 3.50 | 3.48 |
| Ca | 1.12 | 1.14 | 1.15 | 1.18 |
| P | 0.63 | 0.62 | 0.62 | 0.63 |
| Nutrients –analyzed values (%) | | | | |
| DM | 88.00 | 88.50 | 88.00 | 87.30 |
| CP | 21.20 | 21.40 | 21.20 | 21.23 |
| CF | 4.20 | 4.80 | 4.30 | 4.50 |
| EE | 5.10 | 5.20 | 5.40 | 5.30 |
| Ash | 5.60 | 5.90 | 5.60 | 5.700 |
| Ca | 1.67 | 1.60 | 1,62 | 1.70 |
| P | 0.84 | 0.80 | 0.83 | 0.88 |

*[Except for diet D0, the rest of the diet was supplemented with 0.15, 0.20, and 0.25% betaine in $D_1$, $D_2$, and $D_3$, respectively]*

### *Data collection*

Weekly live bird weight, feed intake, and survivability, etc., were taken for data recording. The feed intake and weight gain of the bird were used to calculate the weekly feed conversion ratio (FCR) of the broiler. Records on carcass yield traits, such as dressing percentage and relative weight of breast, thigh, drumstick, shank, abdominal fat, proventriculus, gizzard, heart, liver, pancreas, etc., were also taken on 33d.

### *Sample collection and chemical analyses*

Feed samples collected from the starter and finisher diets were processed in the lab. The proximate components, such as dry matter (DM%), moisture%, crude protein (CP%), crude fiber (CF%), ether extract (EE%), and ash, were analyzed by following standard laboratory methods as instructed by AOAC (2007). Apart from these, atomic absorption and spectrophotometry were used to analyze calcium (Ca%) and phosphorus (P%), respectively.

### *Statistical analyses*

Minitab software (Minitab, 2010) was used to analyze all procured data of this study using the one-way ANOVA procedure. Statistical significance was considered at $P \leq 0.05$.

## Results and Discussion

### *Gross responses of broiler chicken fed a betaine diet*

Except for 33d, the results showed that feed intake (FI) and live weight (LW) of broilers up to 28 days were identical between treatments (P>0.05) (Table 3). The FI and LW of broilers on the D3 diet were (P<0.05) greater than those of others for 28-33 and 1-33 days, respectively. The FCR of broilers was also influenced (P<0.05) during d1-33 (Table 3).

Table 3. Feed intake (FI), live weight (LW) and feed conversion ratio (FCR) of broiler chicken fed a diet supplemented with betaine.

| | Age (days) | Treatment | | | | SEM | P-value |
|---|---|---|---|---|---|---|---|
| | | $D_0$ | $D_1$ | $D_2$ | $D_3$ | | |
| LW(g/b) | 1-14 | 508.62 | 517.29 | 492.00 | 512.81 | 10.188 | 0.828 |
| | 1-21 | 974.60 | 1028.40 | 1004.30 | 1012.10 | 1.799 | 0.596 |
| | 1-28 | 1441.00 | 1524.00 | 1447.40 | 1538.40 | 22.026 | 0.334 |
| | 1-33 | 1742.20 $^{b}$ | 1862.40$^{a}$ | 1784.50$^{a}$ | 1902.40$^{a}$ | 14.261 | 0.015 |
| FI(g/b) | 14-21 | 804.43 | 905.00 | 918.57 | 895.57 | 15.225 | 0.102 |
| | 21-28 | 977.10 | 984.00 | 992.20 | 1035.00 | 13.626 | 0.477 |
| | 28-33 | 715.81$^{b}$ | 631.95$^{c}$ | 659.52$^{c}$ | 741.38$^{a}$ | 12.970 | 0.015 |
| | 14-33 | 2497.40 | 2321.00 | 2570.30 | 2712.00 | 30.600 | 0.136 |
| | 1-33 | 3300.10$^{c}$ | 3210.20$^{b}$ | 3370.10$^{a}$ | 3450.30$^{a}$ | 15.762 | 0.050 |
| FCR | 14-21 | 1.58 | 1.63 | 1.66 | 1.67 | 0.0242 | 0.662 |
| | 21-28 | 1.92 | 1.82 | 2.04 | 1.82 | 0.449 | 0.306 |
| | 28-33 | 2.30 | 1.87 | 2.03 | 2.18 | 0.096 | 0.335 |
| | 14-33 | 2.02 | 1.87 | 1.98 | 1.95 | 0.022 | 0.184 |
| | 1-33 | 1.94$^{a}$ | 1.77$^{c}$ | 1.94$^{a}$ | 1.86$^{b}$ | 0.018 | 0.042 |

*[Data indicate mean values of 10 birds per replicate from days 1-33; $D_0$ refers to the control diet with no supplemental betaine, whereas $D_1$, $D_2$ and $D_3$ diets are supplemented with 0.15, 0.20, and 0.25% betaine, respectively; Values (mean) bearing different superscripts in a row differ significantly at *P<0.05; SEM- standard errors of mean]*

Growth or productivity (body growth, feed intake) and feed efficiency of broilers were ameliorated when the broilers were fed a betaine diet. The findings of our current study coincide with the reports found by earlier investigators (Sun *et al.*,2008; Attia *et al.*, 2009; Nofal *et al.*, 2015; Afrin *et al.*, 2018). The LW of broilers was promoted when a greater amount of betaine was added to diets. The increased LW and better FCR might be due to greater feed consumption, nutrient digestibility, feed utilization, increased metabolic heat production, and absorption of birds on a supplemental diet balanced with amino acids (Hassan *et al.*, 2005; Eklund *et al.*, 2006; Honarbaksh *et al.*, 2007; Bunchasak, 2009).

### *Livability*

The viability (%) of broilers was not affected (P>0.05) by dietary treatment (Figure 1). It denotes that betaine has no adverse impact on the livability of broiler chicken, and we can add betaine in broiler diets without any hesitation as supplemental feed additives. It is reported that betaine has a positive effect on the immune system of broilers and rats (Zhang *et al.*, 1996; Klasing *et al.*, 2002).

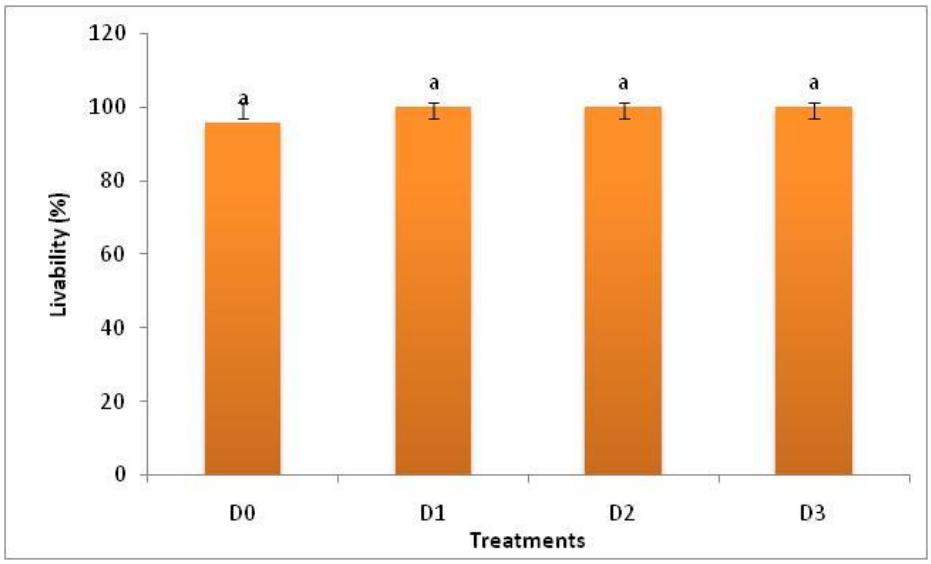



Fig. 1. Livability (%) of broilers fed betaine diets on day 33; Bars with similar letters have no significant differences (P>0.05) between treatments.

Table 4. Meat yield traits (g/100g) of broilers of different body parts fed a diet supplemented with betaine.

| | Treatment | | | | SEM | P-value |
|---|---|---|---|---|---|---|
| | $D_0$ | $D_1$ | $D_2$ | $D_3$ | | |
| Dressing% | 62.64$^{c}$ | 64.94$^{b}$ | 66.91$^{a}$ | 67.58$^{a}$ | 0.146 | 0.050 |
| Breast weight | 22.72 | 25.39 | 26.74 | 27.18 | 0.570 | 0.143 |
| Drumstick weight | 7.17 | 8.57 | 8.57 | 8.49 | 0.129 | 0.432 |
| Thigh weight | 8.50$^{b}$ | 9.09$^{a}$ | 10.25$^{a}$ | 9.17$^{a}$ | 0.118 | 0.050 |
| Wing weight | 4.33 | 4.77 | 5.05 | 5.53 | 0.162 | 0.209 |
| Shank weight | 4.00 | 3.75 | 3.98 | 4.00 | 0.080 | 0.616 |

*[Each value indicates the mean of five replicates consisting of 10 birds per replicate cage at 33 days; Values (mean) bearing different superscripts in a row differ significantly at *P<0.05]*

***Carcass yield traits of broiler chicken***

Only dressing (%) (P<0.05) and thigh weight% (P<0.05) were found to be improved, except for other meat characteristics (breast, drumstick, shank, and wing), as seen in Table 4. Broilers fed the $D_3$ diet had greater dressing yield and thigh weight than those of other groups, which might be due to greater live weight gained in broiler chickens fed the betaine diet. The improved broiler weight on the betaine-fed diet might enhance better dressing percentage as well as other parts of the broiler chicken.

Table 5. Relative visceral organs weight (g/b) of broiler chickens fed a diet supplemented with betaine on day 33.

| | Treatment | | | | SEM | P-value |
|---|---|---|---|---|---|---|
| | $D_0$ | $D_1$ | $D_2$ | $D_3$ | | |
| Proventriculus + gizzard weight | 62.05 | 71.97 | 60.45 | 59.74 | 1.619 | 0.152 |
| Liverweight | 36.96 | 39.57 | 37.27 | 39.56 | 1.804 | 0.921 |
| Heart weight | 8.43 | 8.63 | 8.75 | 9.53 | 0.352 | 0.719 |
| Pancreas weight | 3.21 | 3.32 | 4.27 | 3.57 | 0.192 | 0.373 |

*[Data represent mean values of five replicates consisting of 9 birds on day 33; Treatment $D_0$ refers to control diet, $D_1$, $D_2$ and $D_3$ refer to diets supplemented with 015%, 0.20% and 0.25% betaine, respectively;]*

Yang *et al.* (2016) reported that betaine is often deemed as a carcass modifier for protein deposition, which could promote the quality carcass of broiler chicken. The findings of our study are correlated with the research done by earlier researchers (El-Shinnawy, 2015; Nofal *et al.*, 2015; Afrin *et al.*, 2018; Akter *et al.*, 2020).

***Betaine on the quality of the meat of broiler chicken***

The result indicates that abdominal fat content was unaffected (P>0.05) between treatments in this study (Figure 2).

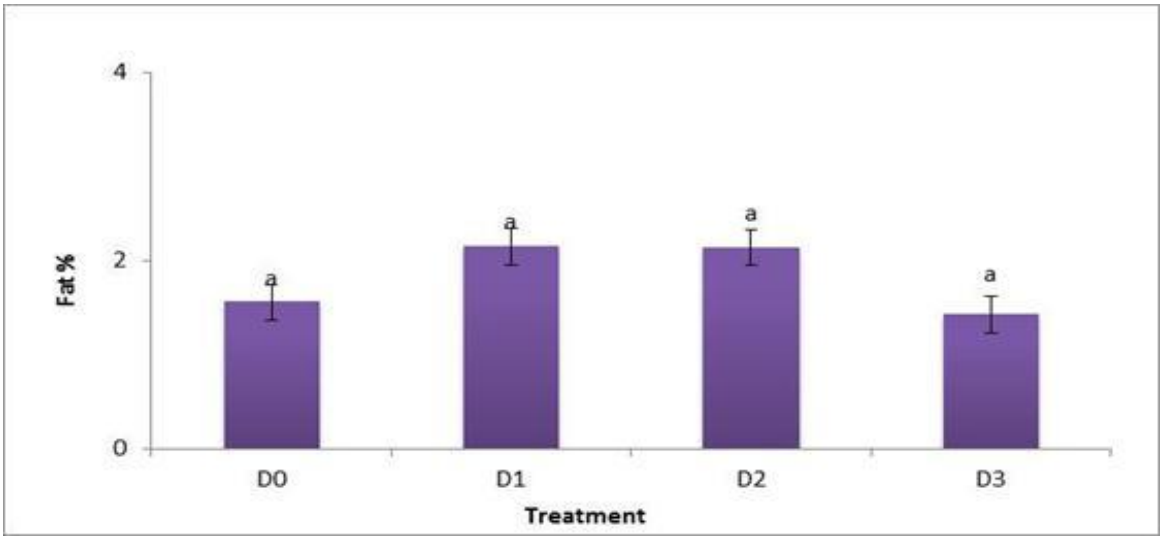



Fig. 2. Abdominal fat (%) of broilers fed betaine diets on day 33; Bars with similar letters have no significant differences (P>0.05) between treatments.

The data showed that broilers fed the $D_3$ diet had lower fat (1.43%) numerically than those of other treatments. The broiler carcass had equal fat content when fed a betaine diet. It denotes that betaine ration does not exhibit any significant impact on fat accretion in the carcass of broilers. Broilers fed a $D_3$ diet attained reduced fat content in their meat, which implies a reduced fat accumulation trend in the betaine-fed diet. The lower the fat%, the greater the quality of meat, which is preferred by consumers worldwide, as it confers increased protein and reduced fat content in the meat. Betaine is deemed a carcass modifier for its nature of fat dispersion, as stated by Eklund *et al.* (2006).

***Gastrointestinal development***

The data shown in Table 5 denote that the relative weights of internal organs (proventriculus, gizzard, liver, heart, and pancreas) of broiler chicken were not influenced (P>0.05) by dietary treatments, which confirms the previous findings done by many earlier researchers (Zhan *et al.*, 2006; Konca *et al.*, 2008; El-Shinnawy, 2015; Hossain *et al.*, 2013, 2014, 2015). Most of the internal organs of broiler chicks occur within 2 weeks of hatching (Nitsan *et al.*, 1991; Iji *et al.*, 2001a,b). The internal fat content decreased significantly by inclusion of betaine in the broiler diet without affecting other internal organs of broiler chickens (liver, gizzard, and giblets), as reported by El-Shinnawy (2015).

## Conclusion

It can be inferred that the overall productivity of broiler-fed betaine-supplemented diet was enhanced, as better body growth, feed efficiency, and dressing yield with reduced fat content were obtained in this study. It can be surmised from the research results that supplemental betaine can be added to broiler diets as an innovative feed additive, which has a better potential for providing reduced fat through improving productivity, greater dressing, and profitability of broiler raising under commercial farming conditions.

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# Strategies and barriers for year-round fruits production in Bangladesh: a literature-based analysis

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**A B S T R A C T**

Bangladesh, an agrarian country with rich agro-ecological diversity, which has substantial potential for expanding fruit production to meet rising nutritional and economic demands. Although more than 100 fruit species are grown nationwide, production is highly seasonal, with nearly 56% of fruits harvested between May and August, resulting in supply gaps, increased imports, and significant post-harvest losses estimated at 26–41%. Per capita fruit intake remains far below the recommended level, reflecting both insufficient availability and inefficiencies in post-harvest handling. This review synthesizes existing literature, national statistics, and global experiences to identify strategic pathways for ensuring sustainable, year-round fruit production in Bangladesh. Key factors limiting continuous production include climatic stresses, lack of suitable off-season varieties, inadequate protected cultivation, poor pollination management, weak extension services, and limited cold-chain infrastructure. The study highlights a set of integrated strategies—crop zoning, varietal improvement, protected cultivation, intercropping systems, precision irrigation and fertigation, and enhanced post-harvest management—that can significantly extend the production window and reduce losses. Successful implementation of these strategies requires coordinated government support, farmer training, research investment, and development of storage and processing facilities. Strengthening market linkages and promoting high-value, climate-resilient fruit varieties can further improve farmer incomes and reduce dependency on imports. The findings emphasize that a holistic, technology-driven, and policy-supported approach is essential to achieve consistent fruit availability, improve national nutrition, and ensure the long-term sustainability of Bangladesh's fruit sector.

**Keywords:** Year-round fruit production, Off-season cultivation, Protected cultivation, Varietal improvement, Post-harvest management, Nutrition security

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## Introduction

Bangladesh possesses diverse agro-ecological zones, fertile soils, and a subtropical climate that collectively support a wide range of fruit species. Fruits such as mango, jackfruit, banana, litchi, guava, papaya, pineapple, and emerging exotic species contribute substantially to agricultural GDP, dietary diversity, and rural employment. Despite this richness, fruit production in Bangladesh is predominantly seasonal, and nearly 56% of total output is harvested during four months between May and August. This seasonality results in supply deficits for the remaining months, leading to high consumer prices, significant post-harvest losses, and dependence on costly imports.

Bangladesh's per capita fruit consumption remains far below WHO-recommended levels, indicating nutritional gaps linked to limited availability. Although BARI, DAE,

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and other institutions have introduced improved fruit varieties, climate-resilient cultivars, and production-enhancing technologies, large-scale adoption by farmers remains insufficient due to inadequate extension services, lack of training, poor access to inputs, and limited infrastructure, such as cold storage and processing facilities. Globally, several countries have successfully addressed seasonal fruit shortages. India has adopted regional crop zoning and hybrid varieties to extend harvest periods; China utilizes greenhouse technologies, precision farming, and cold-chain systems; and Thailand has strengthened post-harvest processing and export-oriented fruit production. These international experiences demonstrate the importance of integrating technology, research, and policy support. Bangladesh can benefit from similar approaches. Protected cultivation, staggered planting, pruning, and hormonal regulation, diversification of varieties, and improved post-harvest value chains can significantly expand the fruit production window. Government initiatives, particularly the DAE's "Year-Round Fruit Production for Nutrition Improvement" project, have made progress, but further scaling is required to achieve nationwide impact.

Final Project Completion Report (PCR) for a government initiative spanning up to 2025 is scheduled for official compilation and formal publication in 2025–2026. Project key achievements in FY2014-15 to 2025 are:

- National fruit output surged from approximately10.608 million tonnes in FY14-15 to 15.033 million tonnes by 2025 (Table 2).
- Previously limited to the summer months, varieties like guava, papaya, and pineapple are now produced and accessible year-round.
- Farmers adopted exotic and high-yielding varieties such as off-season Katimon mangoes, LED-lit dragon fruit, and improved Thai guava.
- Increased domestic yield helped slash the country's reliance on fruit imports by 36%—dropping from 822,000 tonnes in 2022 to 525,000 tonnes in 2025 (DAE, 2026).

In this context, achieving year-round fruit availability is essential not only for food and nutritional security but also for enhancing farmer profitability, stabilizing market supply, reducing reliance on imports, and promoting export competitiveness. This review aims to evaluate existing challenges and outline integrated strategies suited to Bangladesh's climatic and socio-economic conditions to ensure sustainable, year-round fruit production.

## Materials and Methods

This study is based entirely on secondary data collected from published research articles, government reports, theses, and statistical yearbooks relevant to fruit production in Bangladesh. Special emphasis was placed on analyzing seasonal fruit availability across different months, highlighting the dominance of mango, jackfruit, banana, guava, papaya, and pineapple during the peak harvest season (May–August), and the relative scarcity in the remaining months. Off-season fruits in Bangladesh primarily comprise year-round cultivars of staple crops (guava, banana, papaya), newly adopted off-season varieties of high-value summer crops (Katimon mango, BARI kathal-3, watermelon), and technologically manipulated exotic fruits (photoperiod- regulated dragon fruits).

Data on post-harvest losses were primarily drawn from the Bangladesh Agricultural Research Institute (BARI) and the Ministry of Agriculture, which report average losses ranging between 26-41%, depending on fruit type and handling practices (BARI, 2020a; MoA, 2023). These figures were cross-verified with FAO estimates to ensure consistency and reliability (BARI and FAO, 2018).

The time frame of the analysis spans from 2008–2009 to 2023–2024, covering fifteen years of fruit production statistics compiled by the Department of Agricultural Extension (DAE) and the Bangladesh Bureau of Statistics (BBS) (BBS, 2017; BBS, 2023). This period was selected to capture long-term trends in fruit cultivation area, production volume, and seasonal distribution, as well as to evaluate the impact of government-led initiatives such as the "Year-Round Fruit Production for Nutrition Improvement" project.

Information was compiled, tabulated, and presented using descriptive analysis, figures, and tables to evaluate strategies for year-round fruit production. Comparative references were also made to global practices in India, China, and Thailand to contextualize Bangladesh's progress and challenges.

## Results and Discussion

### *Global fruit production leaders (2023)*

Global fresh fruit production in 2023 reached nearly 951.9 million metric tonnes, up from approximately 576.7 million in 2000—highlighting rapid growth in the sector (Statista, 2023). According to Report Linker data**,** the top 10 fruit-producing countries in 2023, along with their estimated production volumes, are:

Table 1. Top ten fruit production countries in the world (2023).

| Rank | Country | Fruit Production (million metric tonnes) |
|---|---|---|
| 1 | China | 267.78 |
| 2 | India | 114.44 |
| 3 | Brazil | 40.15 |
| 4 | Mexico | 25.43 |
| 5 | United States | 23.59 |
| 6 | Indonesia | 22.84 |
| 7 | Spain | 18.95 |
| 8 | Philippines | 17.34 |
| 9 | Italy | 17.08 |
| 10 | Iran | 16.39 |

(Source: ReportLinker, 2023)

These countries together dominate global fruit production, benefiting from large arable land areas and favorable climates. The Trade Policy and Strategy Office (TPSO) estimates that total fruit production in Thailand for 2024 will reach 6.76 million tonnes, reflecting a 2% increase over 2023 (Fructidor, 2024). Another source, citing the Malaysian Agriculture Ministry, indicates a notably higher figure: 1.827 million tonnes of fruit produced in the previous year (implying either 2022 or 2023) (FreshPlaza, 2023).

### *Fruits of Bangladesh*

Fruits are high-value crops in Bangladesh, contributing to nutrition, rural incomes, and diversification away from cereal monoculture. Major fruits (mango, jackfruit, banana, pineapple, guava, papaya, and citrus) occupy a substantial area and show rising production trends in recent years. Yet production remains strongly seasonal — e.g., mango and jackfruit peak in specific months — causing price swings, unmet off-season demand, and lost income opportunities. Year-round production would stabilize incomes, supply urban markets, and support exports. This paper reviews current area/production patterns and presents practical strategies that fit Bangladesh's agro-ecological zones and smallholder structure.

The fruit production scenario of Bangladesh in 2022-23 was 15.033 million metric tonnes in an area of 765000 hectares (7.707% of total cultivable land) (Table 2) (DAE). May to August produce 56% of total production, and the remaining 8 months produce only 44% (Fig. 3). A statement from Bangladesh's Agriculture Ministry (2022–2023) pointed out that post-harvest losses now account for 26–41% of fruit production, significantly hindering efforts to increase per-capita fruit intake (The Financial Express, 13 August 2025). The net amount of fruit available for consumption after accounting for post-harvest losses is 3.91-6.16 million tonnes. Post-harvest management should be prioritized to reduce losses after harvest. Fruit intake per capita is 85g (FAO, 2022) against the requirement for a minimum of 200g, which indicates a 115g deficit (National Guideline, 2020). According to the Bangladesh Bureau of Statistics, fruit production in Bangladesh in 2020-2021, 2021-2022, and 2022-2023 was 5.1387, 5.336, and 5.6588 million metric tonnes, respectively (Table 3). (Source: Yearbook of Agricultural Statistics-2023, Page No. 209)

Abounding with varieties of seasonal fruits, Bangladesh has achieved a remarkable growth in fruit production in the past few years. According to the Food and Agriculture Organization (FAO) of the United Nations, fruit production has increased by 45 percent on average annually for the last 18 consecutive years. In total, the number of edible fruit types is 130 (Roy, 2019). Now,

10-12 fruits, including mango, jackfruit, banana, guava, pineapple, papaya, watermelon, litchi, coconut, dragon fruit, and various types of limes, are grown commercially. About 5 million tonnes of fruits are grown in less than 1 percent of the total crop lands in the country. Almost 63 percent of the total production is mango, jackfruit, and banana. More than 20 types of fruits, such as strawberry, dragon fruit, malta, soursop, mangosteen, rambutan, persimmon, avocado, peach, cherry, and so on, were introduced in the local market in the past decade.

Table 2. Fruit Production in Bangladesh (2008-2009 to 2023-2024).

| Financial Year | Area (ha) | Production (MMT) |
|---|---|---|
| 2008-2009 | 935918 | 10.341 |
| 2009-2010 | 725902 | 10.453 |
| 2010-2011 | 637540 | 10.521 |
| 2011-2012 | 657535 | 10.304 |
| 2012-2013 | 658875 | 10.569 |
| 2013-2014 | 678145 | 9.972 |
| 2014-2015 | 693235 | 10.608 |
| 2015-2016 | 720263 | 11.031 |
| 2016-2017 | 715941 | 12.096 |
| 2017-2018 | 724028 | 12.113 |
| 2018-2019 | 727198 | 12.152 |
| 2019-2020 | 729280 | 12.389 |
| 2020-2021 | 729130 | 12.202 |
| 2021-2022 | 733988 | 14.331 |
| 2022-2023 | 765539 | 15.033 |
| 2023-2024 | 757496 | 14.81 |

(Source: DAE, 2024)

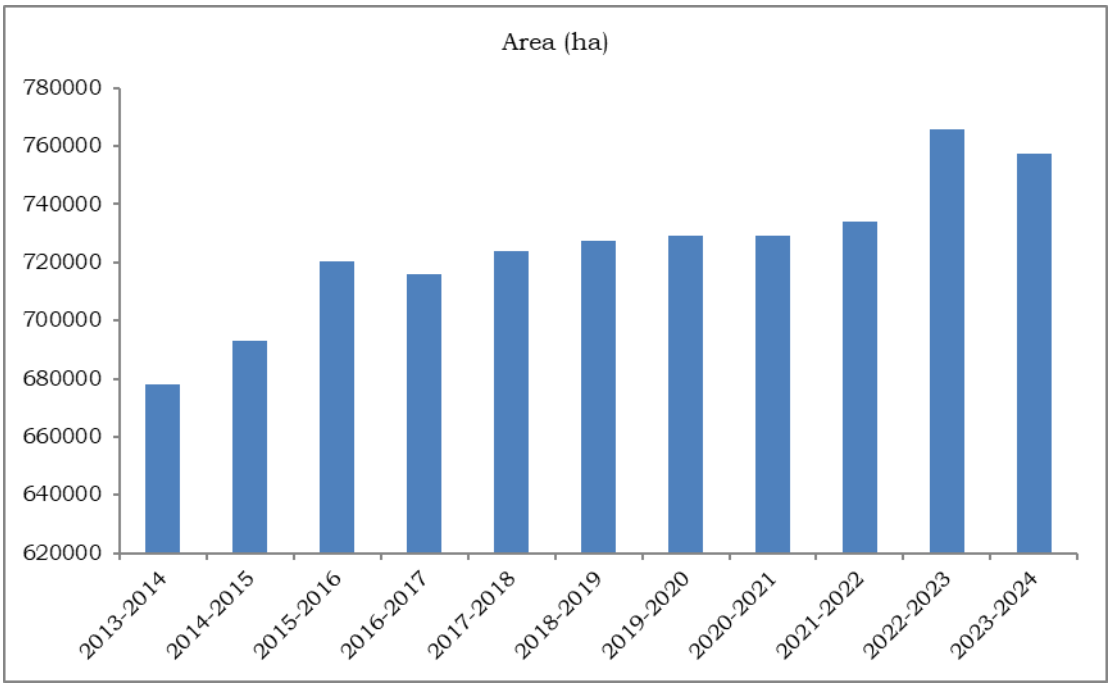



Fig. 1. Fruit Cultivation in Bangladesh (2013-2014 to 2023-2024)
(Source: DAE, 2024)

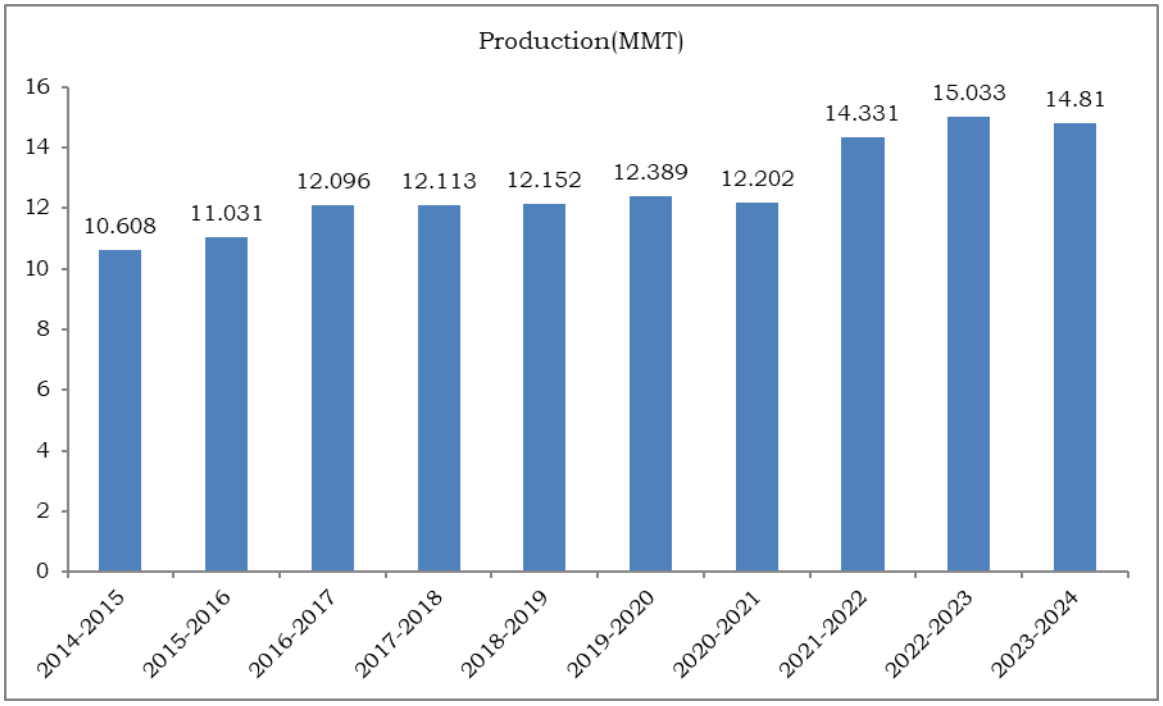



Fig. 2. Fruit Production in Bangladesh (2014-2015 to 2023-2024)
(Source: DAE, 2024)

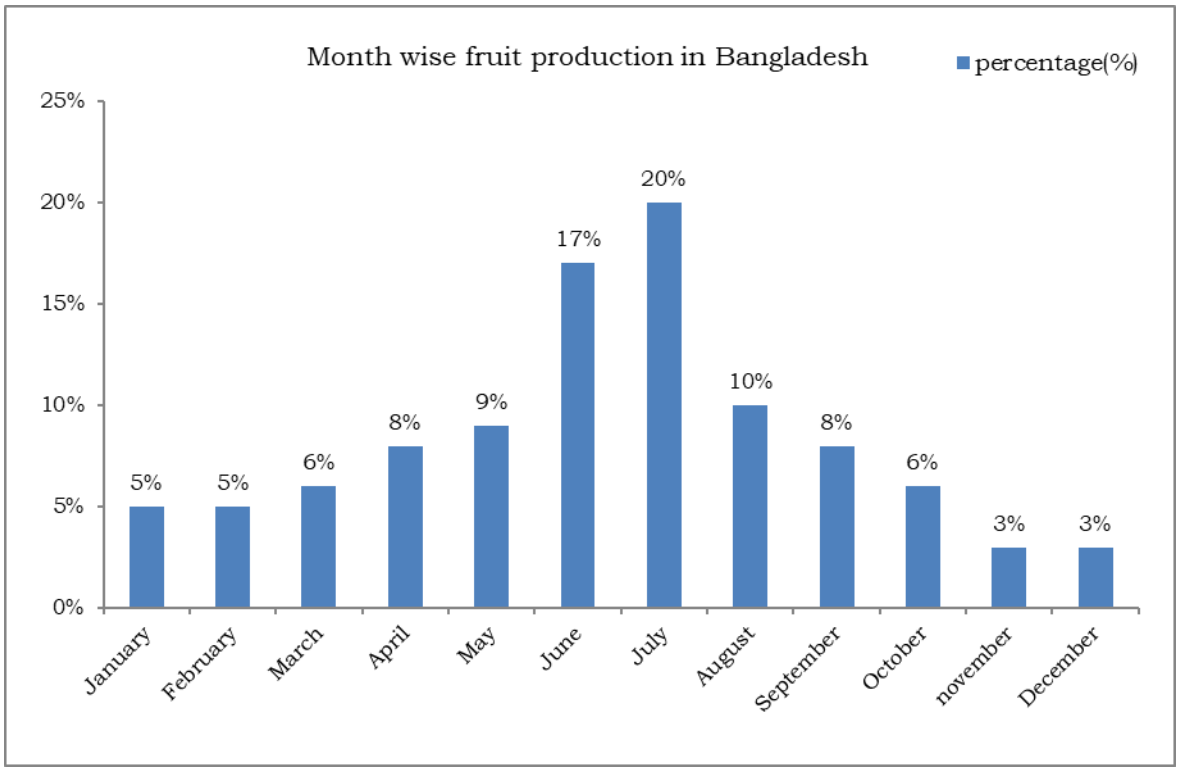



Fig. 3. Month-wise fruit production in Bangladesh.
(Source: DAE, 2024)

Table 3. Area and production of fruit crops in Bangladesh (2020-2021 to 2022-2023).

| Sl. No. | Fruits Crops | 2020-2021 | | 2021-2022 | | 2022-2023 | |
|---|---|---|---|---|---|---|---|
| | | Area (acre) | Production (MT) | Area (acre) | Production (MT) | Area (acre) | Production (MT) |
| ***a. Major Fruits*** | | | | | | | |
| 1 | Banana | 122192.19 | 8261151.76 | 28640.26 | 183438.79 | 122603.38 | 840362.67 |
| 2 | Mango | 286823.00 | 1214597.00 | 299054 | 1207466.00 | 473460.00 | 1482937.04 |
| 3 | Pine Apple | 34246.66 | 208141.88 | 33581.87 | 206164.51 | 32463.36 | 196735.74 |
| 4 | Jackfruit | 44630.00 | 1097001.00 | 69161.00 | 1049890.00 | 75842.04 | 1062302.28 |
| 5 | Papaya | 8414.00 | 125758.00 | 12299.79 | 147350.66 | 17981.81 | 145316.82 |
| 6 | Water Melon | 40860.73 | 345955.44 | 57865.05 | 550367.03 | 58757.44 | 555838.14 |
| 7 | Green Coconut | 62576.00 | 442708.00 | 61083.89 | 458855.24 | 55260.28 | 457088.21 |
| 8 | Litchi | 17279.99 | 87183.80 | 20388.53 | 92958.41 | 21759.53 | 104708.34 |
| 9 | Guava | 58618.00 | 243957.00 | 44742.00 | 244857.00 | 45386.94 | 256105.56 |
| 10 | Jujube | 38652.00 | 107958.00 | 40436.82 | 94877.40 | 17357.80 | 96844.29 |
| Total | | 714292.57 | 12134411.88 | 667253.21 | 4236225.04 | 920872.58 | 5198239.09 |
| ***b. Minor Fruits*** | | | | | | | |
| 1 | Lime & Lemon | 162242.69 | 81604.48 | 30248.22 | 95411.89 | 33087.57 | 99930.87 |
| 2 | Pomelo | 13969.98 | 78665.82 | 13982.12 | 76364.63 | 12800.07 | 71785.28 |
| 3 | Melon (Bangi) | 10097.15 | 47420.17 | 10264.00 | 49572.78 | 10422.49 | 50812.73 |
| 4 | Tamarind | 6279.99 | 9552.60 | 6377.03 | 10238.79 | 5872.06 | 10844.28 |
| 5 | Star Apple | 6649.34 | 12767.32 | 6147.49 | 13363.18 | 5952.58 | 13110.41 |
| 6 | Black Berry | 13751.01 | 56928.21 | 13357.29 | 54135.88 | 12626.15 | 53943.93 |
| 7 | Ata | 1533.50 | 5470.53 | 1525.03 | 5149.13 | 1550.62 | 5034.93 |
| 8 | Dauwa | 74.00 | 1629.50 | 74.21 | 1632.23 | 69.72 | 1464.68 |
| 9 | Lotkon | 407.45 | 2409.60 | 456.71 | 2657.00 | 470.25 | 2746.00 |
| 10 | Karambola | 4198.80 | 14307.39 | 3961.10 | 14931.57 | 3832.83 | 145591.88 |
| 11 | Wood Apple | 17995.18 | 30009.00 | 17975.34 | 29305.75 | 18335.92 | 30441.23 |
| 12 | Green Coconut | 62576.00 | 442708.00 | 61083.89 | 458855.24 | 55260.28 | 457088.21 |
| 13 | Olive | 5205.25 | 18848.36 | 5101.22 | 18496.40 | 4794.43 | 18825.97 |
| 14 | Hog Palm | 11417.00 | 42527.00 | 11737.00 | 43801.12 | 11261.25 | 43880.78 |
| 15 | Amloki | 1627.17 | 2820.42 | 1638.84 | 2609.36 | 1456.41 | 2434.90 |
| 16 | Chalta | 5106.77 | 10154.05 | 3376.84 | 10679.98 | 3186.75 | 10210.44 |
| 17 | Dalim | 670.64 | 1411.39 | 790.40 | 1442.64 | 815.94 | 1548.79 |
| 18 | Karamcha | 27.00 | 166.65 | 60.19 | 155.12 | 64.38 | 159.80 |
| 19 | Safeda | 1683.00 | 6573.45 | 1635.52 | 6468.34 | 1661.43 | 6808.56 |
| 20 | Sarifa | 840.42 | 2229.42 | 810.90 | 1663.03 | 787.20 | 1768.63 |
| 21 | Water Fruit | 405.80 | 1899.35 | 453.20 | 2027.03 | 475.34 | 2304.88 |
| Total | | 326758.14 | 870102.71 | 191056.54 | 898961.09 | 184783.67 | 1030737.18 |
| ***c. Promising Foreign Fruits*** | | | | | | | |
| 1 | Dragon Fruit | 349.69 | 1138.70 | 717.53 | 3153.84 | 1135.40 | 5959.29 |
| 2 | Malta | 13256.00 | 6501.71 | 4456.23 | 10269.14 | 4184.23 | 8886.00 |
| Total | | 13605.69 | 7640.41 | 5173.76 | 13422.98 | 5319.63 | 14845.29 |
| Grand Total | | 994042.25 | 5138703 | 804653.59 | 5336203.58 | 1058239.79 | 5658854 |
| | | 402446.07 ha | 5.13870 MMT | 363804.05 ha | 5.336203 MMT | 428437.16 ha | 5.658854 MMT |

(Source: BBS, 2023)

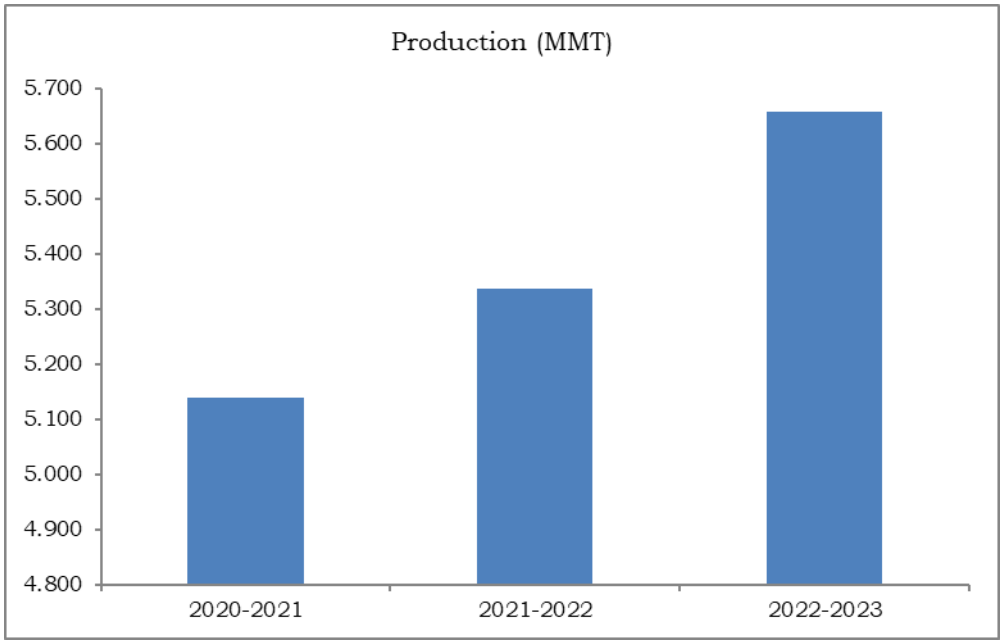



Fig. 4. Fruit Production in Bangladesh (2020-2021, 2021-2022 and 2022-2023) (Source: BBS, 2023)

The analysis reveals a steady increase in fruit production over the past decade, with notable growth after 2016. The rising trend reflects improved varietal development, expanded orchard establishment, and government-led programs promoting fruit cultivation. However, production remains concentrated in specific seasons, causing annual shortages. Post-harvest losses estimated at 26-41% pose a major barrier to year-round availability. Improved storage, cold-chain systems, and processing industries are essential to minimize these losses.

Adopting early, mid, and late-maturing varieties can significantly extend the harvesting window. Protected cultivation technologies, including poly-houses and net-houses, offer opportunities for off-season production of high-value fruits such as papaya, strawberry, and dragon fruit. Intercropping systems, such as integrating banana, pineapple, and papaya, can ensure continuous income while establishing long-term orchards. Climate-smart practices, including drip irrigation, fertigation, mulching, and integrated pest management (IPM), can enhance productivity and resilience. Successful implementation requires strong extension services, farmer training, financial incentives, and improved policy support. Investments in rural collection centers, cold storage, and digital market linkages are necessary to ensure a stable supply chain and support year-round fruit availability.

***Barriers to year-round fruit production in Bangladesh***

*Climate and Environmental Constraints*

- Seasonal Weather Extremes- High temperatures in heavy monsoon rains and cold waves in winter limit continuous flowering and fruiting for many species.
- Flood and Waterlogging – Damage root systems and cause crop failure in low-lying areas.
- Cyclones and Storms – Common in coastal regions, causing severe damage to perennial fruit trees.
- Soil Salinity – Particularly in coastal zones, it reduces fruit yield and quality.
- Pest and Disease Outbreaks- Seasonal peaks of fruit flies, mealy bugs, fungal infections, etc.

*Technical and Agronomic Barriers*

- Unavailability of suitable varieties – Few high-yielding, climate-resilient, off-season varieties are available for mango, guava, litchi, etc., but other fruit varieties are unavailable for year-round cultivation.
- Insufficient research on year-round fruit production, poor adoption, and staggered planting to adjust harvest time.

- Limited adoption of protected cultivation- greenhouses, net-houses, and rain shelters are rare outside research.
- Poor pollination management- Lack of managed bee pollination during offseason flowering.
- Lack of skilled manpower- Technology was hampered due to a lack of skilled manpower.

*Socio-Economic and Institutional Barriers*

- High production cost- Offseason production often requires irrigation, fertilizers, and pest control investment beyond the farmer's capacity.
- Low farmer awareness- Limited knowledge about techniques like grafting, mulching, and micronutrient modification.
- Credit and financing issues- Limited access to affordable loans for fruit orchard establishment and maintenance.
- Market price fluctuation- Off-season fruits sometimes face poor demand if consumers are not accustomed to them.

*Post-harvest and Infrastructure*

- Poor cold chain facilities- Limited refrigerated transport and storage means off-season harvests can't be stored for market timing.
- Inadequate processing industries- Low capacity to turn fruits into value-added products.
- Weak supply chain coordination- Delays and handling losses in getting products from the orchard to the consumer.

*Policy and Extension Gaps*

- Limited government incentives- Subsidies or supports for off-season fruit production are not widespread.
- Weak extension services- Farmers often lack hands-on training and demonstration plots for year-round production methods.
- Slow varietal release process- New varieties from research stations take years to reach farmers.

***Strategies for year-round fruit production in Bangladesh***

*Crop Diversification and Zoning*

- Select fruits based on agro-ecological zones (e.g., mango in Rajshahi, pineapple in Sylhet, citrus in Mymensingh, coconut in coastal areas).
- Diversify orchards with early, mid, and late-maturing varieties to ensure continuous availability.

*Varietal Improvement and Extended Harvesting*

- Introduce early- and late-season varieties of mango, litchi, banana, and guava to extend the harvesting window.
- Use off-season cultivation techniques (grafting, pruning, hormonal treatment, bagging, mulching).
- Promote high-yielding and climate-resilient fruit varieties developed by BARI.

*Protected Cultivation and Climate-Smart Practices*

- Use polyhouse/greenhouse technology for papaya, strawberry, and dragon fruit.
- Drip irrigation, mulching, and fertigation to maintain yield during dry seasons.
- Climate-adaptive management to minimize risks of cyclones, drought, and salinity.

Table 4. BARI Recommended Fruit Intercropping Patterns (General Guidelines).

| Main Fruit Crop (Young) | Intercrop Fruit/Short-term Crop | Spacing/Pattern Recommended |
|---|---|---|
| Mango (e.g., BARI Aam-3) | Papaya, Pineapple, Banana | 2-3 rows in between mango rows |
| Litchi | Papaya, Banana, Pineapple | 1-2 rows depending on tree age |
| Citrus (Malta/Mandarin) | Pineapple, Papaya | Paired row system |
| Pineapple (Main) | Papaya, Mukhikachu | 100% Pineapple + 66% Papaya |
| Banana | Papaya, Pineapple | In the early stages of banana. |

(Source: BARI, 2020b)

*Intercropping and Multi-storied Orchard Systems*

- Multi-storied fruit orchards (coconut → banana/papaya → pineapple/ginger) optimize land use and provide seasonal harvests.

*Improved Post-Harvest and Storage Facilities*

- Establish cold storage chains for perishable fruits (mango, litchi, guava).
- Promote processing industries (juice, jam, dried fruit) to reduce post-harvest loss.
- Community-based storage hubs at the rural level.

*Extension and Farmer Training*

- Capacity building through farmer field schools (FFS).
- Training on pruning, grafting, IPM (Integrated Pest Management), and GAP (Good Agricultural Practices).

*Policy and Institutional Support*

- Government subsidies/incentives for fruit orchard establishment.
- Public-private partnerships for export-oriented fruit production.
- Strengthening market linkages and digital platforms for farmer-to-consumer sales.

*Research and Innovation*

- Strengthen BARI, BFRI, and universities to research new fruit varieties and off-season production techniques.
- Promote tissue culture and biotechnology (e.g., banana, papaya).

## Conclusion

Year-round fruit production in Bangladesh is achievable through integrated strategies combining varietal improvement, protected cultivation, crop zoning, climate-smart technologies, and improved post-harvest management. Ensuring continuous fruit availability will enhance nutrition, reduce imports, stabilize markets, and improve rural livelihoods. Comprehensive policy support, investment in cold-chain infrastructure, and stronger research–extension partnerships are essential to sustain the momentum in fruit production growth.

### Recommendations

- Crop diversification and crop zoning.
- Promote early- and late-maturing varieties for extended harvesting.
  - Expand protected cultivation using low-cost structures.
- Intercropping and multi-storied orchard system.
  - Strengthen farmer training in pruning, grafting, and IPM.
  - Invest in cold-chain infrastructure and rural processing centers.
  - Enhance collaboration among research institutes, extension agencies, and private sector actors.
- Strengthen research and innovation.

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# Enhancing beetroot (*Beta vulgaris* L) growth and soil quality through vermicompost–fertilizer integration in coastal saline soil

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**A B S T R A C T**

In Bangladesh's coastal areas, soil salinity affects both soil health and agricultural output. An experiment was conducted to assess the combined effects of vermicompost and inorganic fertilizers on improving saline soil properties and the growth performance of beetroot at the Agricultural Research Field, Noakhali Science and Technology University, Noakhali, Bangladesh. The experiment followed a Randomized Complete Block Design with nine treatment comprises of, $T_1$ (Control); $T_2$ (100% RDF* + 0 t ha$^{-1}$ VC); $T_3$ (50% RDF* + 0 t ha$^{-1}$ VC*); $T_4$ (50% RDF* + 2.5 t ha$^{-1}$ VC*); $T_5$ (50% RDF* + 5 t ha$^{-1}$ VC*); $T_6$ (50% RDF* + 10 t ha$^{-1}$ VC*); $T_7$ (100% RDF* + 2.5 t ha$^{-1}$ VC*); $T_8$ (100% RDF* + 5 t ha$^{-1}$ VC*); $T_9$ (100% RDF* + 10 t ha$^{-1}$ VC*). The highest Plant height 49.11 cm, maximum number of leaves per plant 12.27, and maximum leaf area 316.23 (cm$^2$) per plot were recorded with the T8 treatment, while the maximum green beetroot yield 6.40 t ha$^{-1}$) and maximum root yield 9.37 t ha$^{-1}$) were found to be the highest with $T_9$. Vermicompost application lowered soil electrical conductivity (EC) from 2.94 to 0.98 dS m$^{-1}$, indicating improved soil conditions and reduced salinity stress. The untreated group ($T_1$) had the poorest outcome across all variables. These data suggest that integrating vermicompost (5-10 t ha$^{-1}$) with standard fertilizer doses significantly enhances beetroot growth, yield, and soil quality under coastal saline conditions, offering an effective approach to sustainably producing vegetables in Noakhali and other saline areas. Additional research is encouraged to corroborate these results across a more extensive agroecological context.

**Keywords:** Beetroot, *Beta vulgaris*, Vermicompost, Saline soil

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## Introduction

Soil salinity is a serious issue for agriculture as it impacts physical growth factors, including root size, biomass, and yield, by causing osmotic stress, ion imbalance, decreased nutrient availability, and agricultural sustainability (AbdElgawad *et al.*, 2016; Machado and Serralheiro, 2017; Khatun *et al.*, 2019; Munns and Tester, 2008). Salinity levels above 4 dS m$^{-1}$ during the dry season can severely limit vegetable cultivation in coastal Bangladesh (SRDI, 2022). Root and tuber crops are typically sensitive to salinity; however, beetroot (*Beta vulgaris* L.) is rich in vitamins, minerals, and antioxidants and is highly adaptable to Bangladesh's varied agro-ecological conditions.

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Beetroot is a globally farmed root vegetable and edible plant used for sugar production, fodder, natural dye, and human consumption (Talucder *et al.*, 2025). Beetroot is among the top ten vegetables with the highest concentrations of phenolic compounds and antioxidant activity. Variety, cultivation environment, and morphological characteristics all affect red beetroot's chemical composition and nutritional value. Beetroot is easily maintained in fields. It demonstrates high yield and rapid development and is generally free of complications and pests (Brar *et al.*, 2015; Feizi *et al.*, 2018; dos S. Baião *et al.*, 2020). Beetroot grows well in saline soils when integrated with organic amendments, such as vermicompost, and recommended fertilizer (Kibatu and Mamo, 2014; Chaves *et al.*, 2009). Beetroot can be a good test crop for examining how vermicompost impacts growth and yield performance in saline soil conditions due to its natural resistance to drought and salt (Uddin *et al.*, 2016) and the noticeable effects of vermicompost in lowering soil salinity and enhancing beetroot's leaf production, chlorophyll content, and vegetative growth (Mia and Rashid, 2023; Tahjib-UI-Arif *et al.*, 2019).

Organic amendments, particularly vermicompost, have demonstrated great potential for mitigating the negative effects of salinity on plant development. Vermicompost improves soil physical properties, enhances nutrient availability, and can reduce salt accumulation in the topsoil (Khatun *et al.*, 2019). Previous studies have demonstrated that the application of vermicompost in saline environments can substantially increase soil organic matter, improve soil pH, and enhance the availability of essential nutrients across various cropping systems, including water spinach and wheat (Lazcano and Dominguez, 2011). Co-application of organic amendments with chemical fertilizers has also been shown to improve soil structural stability, stimulate beneficial microbial communities, and ultimately increase plant biomass and yield (Biancardi *et al.*, 2012; Rozema *et al.*, 2015). Salt-affected sedimentary soils have shown that applying vermicompost increases nutrient content and promotes plant growth while decreasing electrical conductivity (EC) and bulk density of the soil (Arancon *et al.*, 2004; Joshi *et al.*, 2020).

Although beetroot can be grown effectively in saline soils with appropriate fertilizer management, its cultivation remains very limited in Bangladesh, especially in the Noakhali region, and a comprehensive study of its potential yield under these conditions is lacking. Similarly, combining vermicompost and inorganic fertilizers has been shown to increase crop yield and soil fertility (Melak *et al.*, 2025), yet studies assessing their combined effects on beetroot growth and physical parameters are lacking in the coastal agroecosystem of Noakhali. The present study is therefore designed with the hypothesis that the integrated use of vermicompost and inorganic fertilizers will enhance the physical growth parameters of beetroot while reducing salinity stress, compared to no fertilization under coastal saline conditions.

## Materials and Methods

### *Study area and sample collection*

The experiment was carried out at Noakhali Science and Technology University's Agricultural Investigation Field in Noakhali, Bangladesh (Latitude: 22°47′31″ N; Longitude: 91°06′03″ E) from November 2024 to February 2025 in the agro-ecological region of the Young Meghna Estuarine Floodplain (AEZ-18). In the current investigation, initial soil samples were randomly collected from six sites at depths of 0-20 cm using a hand auger and then thoroughly mixed. The initial soil was silt loam in texture, slightly acidic in reaction, and slightly saline (Table 1 and 2).

Table 1. Physical and chemical properties of the initial soil under study.

| Parameters Values | Sub-surface (0-20 cm depth) |
|---|---|
| Textural class | Silt loam |
| pH(1:2.5) | 6.94 |
| EC (dS/m) | 2.92 |

Table 2. Salinity classes according to the SRDI (2010).

| Salinity Class | EC (dS/m) |
|---|---|
| Non-saline | 0-2 |
| Slightly saline | 2-4 |
| Moderately saline | 4-8 |
| Highly (or strongly) saline | 8-16 |
| Very / Extremely saline | >16 |

***Land preparation and experimental design***

A mechanical tiller was used to prepare the area thoroughly, followed by a harrow and a shovel. Three replications were used in the Randomized Complete Block Design (RCBD) experiment. The experiment consisted of nine treatments, viz., $T_1$ (Control); $T_2$(100% RDF* + 0 t ha$^{-1}$ VC); $T_3$ (50% RDF* + 0 t ha$^{-1}$ VC*); $T_4$ (50% RDF* + 2.5 t ha$^{-1}$ VC*); $T_5$ (50% RDF* + 5 t ha$^{-1}$ VC*); $T_6$ (50% RDF* + 10 t ha$^{-1}$ VC*); $T_7$ (100% RDF* + 2.5 t ha$^{-1}$ VC*); $T_8$ (100% RDF* + 5 t ha$^{-1}$ VC*); $T_9$ (100% RDF* + 10 t ha$^{-1}$ VC*). The size of each treatment was kept at 1.0 m × 1.0 m. Each treatment was 20 cm high, with 8 cm-deep drainage around each plot to restrict lateral runoff of irrigation or rainfall water. The distance between the two blocks and the two plots was maintained at 0.5 m. Plant spacing was 0.25 m. During the final land preparation, vermicompost was applied at the prescribed treatment rates. According to Islam *et al.* (2017), inorganic fertilizers were applied at the recommended rates.

* RDF = Recommended dose of fertilizer
*VC = Vermicompost

***Seed collection and germination test***

An approved high-yielding variety of Beetroot (*Beta vulgaris* L) was used in this experiment. A seed that germinates quickly has a higher chance of sprouting in the field. Two distinct petridishes were obtained and sterilized with ethanol in order to determine the germination percentage. Seeds that had been soaked in water were set out on the tissue paper in the petridishes and left at room temperature for a whole day. In the Beets from 50 seeds, 46 seeds germinated, for a germination rate of 92%.

***Observation and data collection***

Data on several parameters were collected using the sample plants during the experiment, such as the number of leaves per plant, the length, width, and area of the leaves (cm$^2$), the height of the plant (cm), the initial weight of the roots per plant (g), the root weight per plot (kg), and the root weight (tons per hectare). At 45, 80, and 100 days after sowing (DAS), five randomly chosen plants from each plot had their height, number of leaves per plant, leaf length, and leaf breadth measured in centimeters (cm). Five randomly chosen plants from each plot were oven-dried, and the dry matter content of their roots was measured.

*Intercultural practices*

Numerous intercultural techniques, including mulching, watering, weed control, and earthing up, were used to enhance plant growth and development. At 30 days after sowing (DAS), a hoe was used to loosen the soil. After the seeds were sown, weeding and thinning were carried out at 8, 25, 45, 65, and 80 days. At 30 and 45 DAS, Indofil M-45 (2 g L$^{-1}$) was sprayed to prevent fungal assault.

*Harvesting*

Five samples were uprooted from each plot individually after 100 DAS. After that, the plants were rinsed with water to remove dead and dried plant parts. The plant samples were then taken to the threshing floor to record data.

*Collection of post-harvest soil to determine pH and EC*

The soil samples were taken between 0 and 20 cm below the surface. Three subsample sets for each sampling site were collected and carefully combined. After being air-dried, ground, and thoroughly mixed, the combined samples were sieved through a 2 mm sieve and then placed in a sterilized plastic container for analysis. The pH of the soil was measured using a glass electrode pH meter. According to Jackson (1962), the soil-to-water ratio in the suspension was maintained at 1:2.5. To measure the sample's electrical conductivity (EC), soil and distilled water were mixed at a 1:5 (w/v) ratio and stirred for 30 minutes. A digital EC meter standardized with a 0.01 N KCl solution at 25 °C was used to measure the EC of the filtrate after the suspension had been filtered through Whatman No. 42 filter paper (Page *et al.*, 1982).

***Statistical analysis***

According to Gomez and Gomez (1984), the analysis of variance (ANOVA) was used to statistically analyze all obtained data. The Least Significant Difference (LSD) test was used to assess the significance of mean differences at the 5% and 1% significance levels.

## Results and Discussion

***Effect of various combinations of vermicompost and inorganic fertilizers on post-harvest soil pH and EC***

The present study revealed that integrating vermicompost with inorganic fertilizer significantly reduced soil EC, indicating reduced salinity stress on plants and increased nutrient availability (Nell *et al.*, 2014), with minimal effect on pH. The lowest EC level (0.98 dS/m) (Fig. 1) was observed at treatment $T_6$, which did not differ significantly ($p > 0.05$) from T5, T8, and $T_9$. However, the highest EC (2.92 dS/m) was observed in the control ($T_1$). This outcome shows that vermicompost has a beneficial effect in lowering salinity stress. These findings were correlated with the experiment of Petmuenwai *et al.* (2024). In highly salinized soil, they showed that the addition of vermicompost and organic amendments resulted in a lower EC (0.30-5.98 dS/m) than the control treatments. Wang *et al.* (2017) conducted an experiment on tomato and recommended vermicompost as a fertilizer to improve tomato yield and soil quality. They reported that during the final sampling period, EC was lower in the vermicompost treatment. The greatest improvement in saline-alkaline soil was achieved by Ai *et al.* (2023), which improved pH and conductivity.

Soil pH was highest (7.5) where EC was low (Fig. 1). One possible explanation is that higher EC values indicate higher ion content, which pushes hydrogen ions in the soil away and lowers the pH. The findings of the present study are also supported by Debi *et al.* (2019), who reported a negative correlation between pH and EC, a pattern also suggested by many other researchers (Shabbir *et al.*, 2014; Ouhadi and Goodarzi, 2007). The lowest soil pH (6.96) (slightly acidic) was recorded in treatment $T_1$, which differed significantly ($p < 0.05$) from the treatments receiving vermicompost. This is because vermicompost contains humic compounds and exchangeable cations ($Ca^{2+}$, $Mg^{2+}$, and $K^{+}$) that buffer soil acidity and enhance soil chemical balance. Lalitha *et al.* (2000), Chaoui *et al.* (2003), and Joshi *et al.* (2015) reported similar patterns, indicating that the application of vermicompost increased soil pH and improved soil fertility in acid-prone soils.

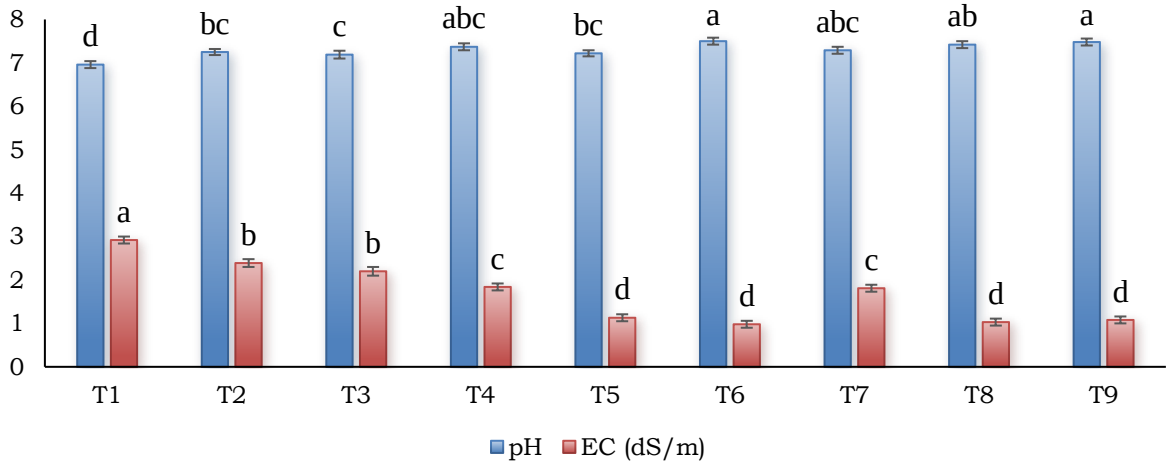



Fig 1. Effect of different fertilizer treatments on post-harvest soil pH and electrical conductivity (EC). A one-way ANOVA was carried out, followed by Tukey's post-hoc test, to see if there were any significant variations in soil pH and EC between the treatments. Significant differences between treatments are shown by different letters above the bars ($p < 0.05$).

***Effect of various combinations of vermicompost and inorganic fertilizers on the growth of beetroot***

*Plant Height*

The combined effects of organic and inorganic fertilizers on plant height at various stages of growth are depicted in Figure 2. At 45 days after sowing (DAS), there was a significant difference ($p < 0.05$) between the treatments. The plant height in $T_1$ (Control) was the lowest (13.96 cm) and differed greatly from those of the other treatments ($T_2$–$T_9$). However, at 80 and 100 DAS, no significant differences were observed. This suggests that the difference in plant height decreased at later growth stages, even if fertilizer application affected early plant growth (Mia and Rashid, 2023). These findings are also supported by Du *et al.* (2021). They recorded that during early and mid-growth stages, plant height increased significantly with fertilizer rate. However, by the 60th day, there were insignificant differences in plant height among treatments.

The maximum plant height at 45 DAS (21.42 cm), 80 DAS (49.11 cm), and 100 DAS (47.26 cm) was recorded in treatment T9 (100% RDF + 10 t $ha^{-1}$ VC) over the control. The influence of organic manure on the vegetative growth of maize was examined by Abubakar and Ali (2018). They found that applying more manure resulted in higher plant heights, which was superior to applying inorganic fertilizer. The present study revealed that the survival rate was significantly higher in vermicompost-treated soil. It has been noted that vermicompost, a stable organic compound produced by microbes and earthworms, increases greenhouse crop yields and plant germination (Khatun *et al.*, 2019). Similar results were reported by Majhi *et al.* (2024). The authors observed a significantly increased plant height (38.30 cm) in beetroot with the incorporation of vermicompost, compared with the control.

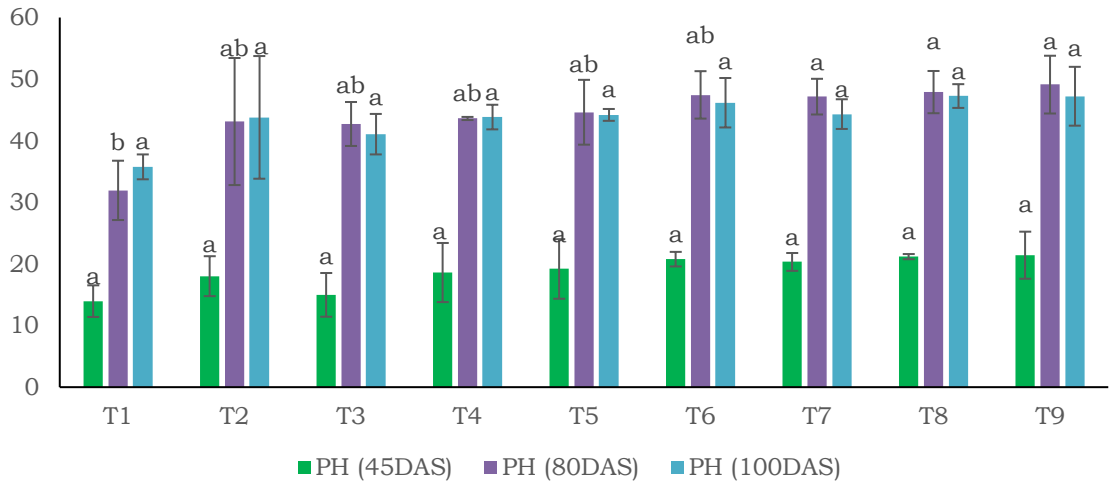



Fig. 2. Response of plant height at various treatments as affected by vermicompost application. A one-way ANOVA was conducted, followed by Tukey's post hoc test, to assess whether there were significant differences in plant height among the treatments. Significant differences between treatments are shown by different letters above the bars ($p < 0.05$).

*Number of Leaves*

The result indicated that Leaf number per plant increased significantly from 45 DAS through 80 DAS to 100 DAS ($P < 0.05$). At 45 DAS, the control ($T_1$) had a significantly lower leaf number (3.35/plant) compared with several vermicompost treatments (Majhi *et al.*, 2024). However, as shown in Figure 3, except for the control, the differences among the other treatments were not statistically significant at 45 DAS. Since the plants are still in the early stages of establishment, the effects of treatment and environmental changes have not fully developed, which explains the comparatively low variability at 45 DAS. Likewise, by 100 DAS, plants might have reached the mature vegetative stage under the specified conditions, thereby reducing treatment heterogeneity and differential responses. In contrast, the fast-growing period at 80 DAS

increases variability among plants and highlights treatment differences. At 80 DAS, the highest number of leaves (11.18 per plant) was recorded in treatment $T_9$ (100% RDF* + 10 t ha$^{-1}$ VC*) followed by $T_8$ (10.37) (100% RDF* + 5 t ha$^{-1}$ VC*), which was significantly greater than the control (5.80), indicating that vermicompost is particularly beneficial during the vegetative phase, though its marginal benefit diminishes as plants approach maturity.

These results align with recent research by Laužike *et al.* (2025), which found that organic amendments such as vermicompost considerably increased leaf number (e.g., in lettuce) by 6.8–16.6% over the control during the vegetative stage, but that variability decreased as plants matured. Similarly, Mia and Rashid (2023) reported the highest number of leaves (10.10) in beetroot at 70 DAP (Days After Planting) with the highest doses of organic amendment application.

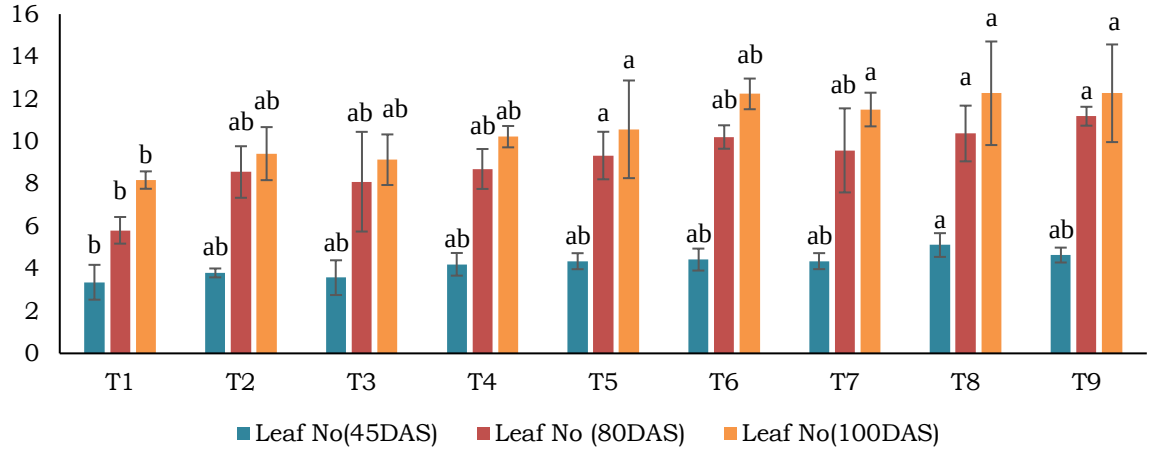



Fig. 3. Response of No. of leaves at various treatments as affected by vermicompost application. A one-way ANOVA was conducted, followed by Tukey's post hoc test, to assess whether there were significant differences in the number of leaves among the treatments. Significant differences between treatments are shown by different letters above the bars ($p < 0.05$).

*Leaf Area*

Figure 4 reveals that the differences among treatments at 45 DAS are statistically nonsignificant. This suggests that the application of vermicompost didn't significantly affect the rate of leaf expansion during the early vegetative stage. Early growth is often governed by seed reserves and initial soil nutrient status, and the slow mineralization rate of vermicompost delays nutrient availability at this stage (Edwards *et al.*, 2011). Similarly, Atiyeh *et al.* (2002) observed that the effects of vermicompost on vegetative growth parameters (such as leaf area and biomass) in tomato and marigold were minimal during the early stages but became significant later as nutrient release intensified.

However, significant differences ($p<0.05$) among treatments are evident at 80 DAS and 100 DAS. Treatments that received vermicompost, specifically $T_8$ (100% NPKS ha$^{-1}$ + 5 t ha$^{-1}$ VC) and $T_9$ (100% RDF* + 10 t ha$^{-1}$ VC*), showed increased leaf area, indicating that vermicompost application enhanced leaf expansion due to improved nutrient supply, better soil aeration, and microbial stimulation (Yadav *et al.*, 2017). At 80 and 100 DAS, $T_9$ (100% NPKS ha$^{-1}$ + 5 t ha$^{-1}$ VC) and $T_8$ (316.23 cm$^2$) had the highest leaf area per plant, respectively, which was significantly greater than the control. The second highest (Fig. 3) was obtained by $T_9$ (270.50 cm$^2$) at 100 DAS, whereas the minimum was observed in treatment $T_1$ (Control).

The above results are comparable to those of Kondal *et al.* (2024), who discovered that beets with 100% organic manure had the largest leaf area. The outcomes of this study are corroborated by Jagadeesh *et al.* (2018), who applied poultry manure to beetroot plants to improve their physical growth. According to Joshi *et al.* (2020), beetroot plants treated with 50% RDF + vermicompost (5 t ha$^{-1}$) had significantly higher leaf area index compared to the control due to increased N and K uptake, which correlates with our findings.

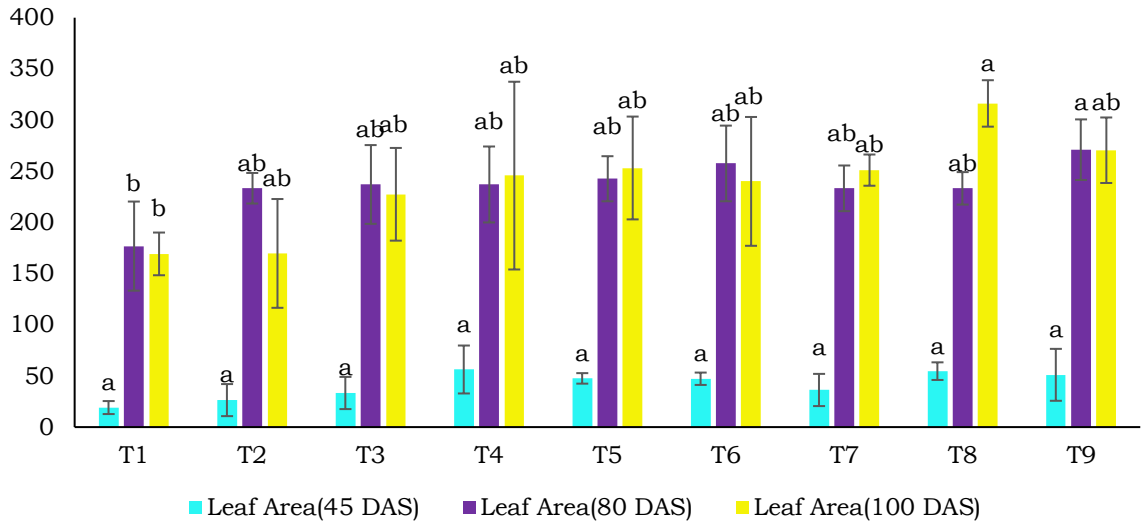



Fig. 4 Response of leaf Area at various treatments as affected by vermicompost application. A one-way ANOVA was conducted, followed by Tukey's post hoc test, to assess whether leaf area differed significantly among the treatments. Significant differences between treatments are shown by different letters above the bars ($p < 0.05$).

*Effect of various combinations of organic and inorganic fertilizers on the yield of beetroot*

Vermicompost greatly improves beetroot growth and production under saline conditions. This could result from the application of organic amendments, which raise the concentration of Ca2+ in the soil solution, replace Na+, and lower salinity (Khatun *et al.*, 2019). The maximum green beetroot yield (6.4 t ha$^{-1}$) was recorded in $T_9$ (100% NPKS ha$^{-1}$ + 10 t ha$^{-1}$ VC) followed by $T_8$ (100% NPKS ha$^{-1}$ + 5 t ha$^{-1}$ VC) (5.10 t ha$^{-1}$), which was statistically significant ($p < 0.05$) compared with the untreated control (0.77 t ha$^{-1}$) (Fig. 5). This correlates with the findings of Maloisane and Kayombo (2022). They reported that high vermicompost rates (e.g., 30 t ha$^{-1}$) substantially increased vegetative growth, fresh root and leaf yield of beetroot. This is also supported by Patidar *et al.* (2025) and Kibatu and Mamo (2014).

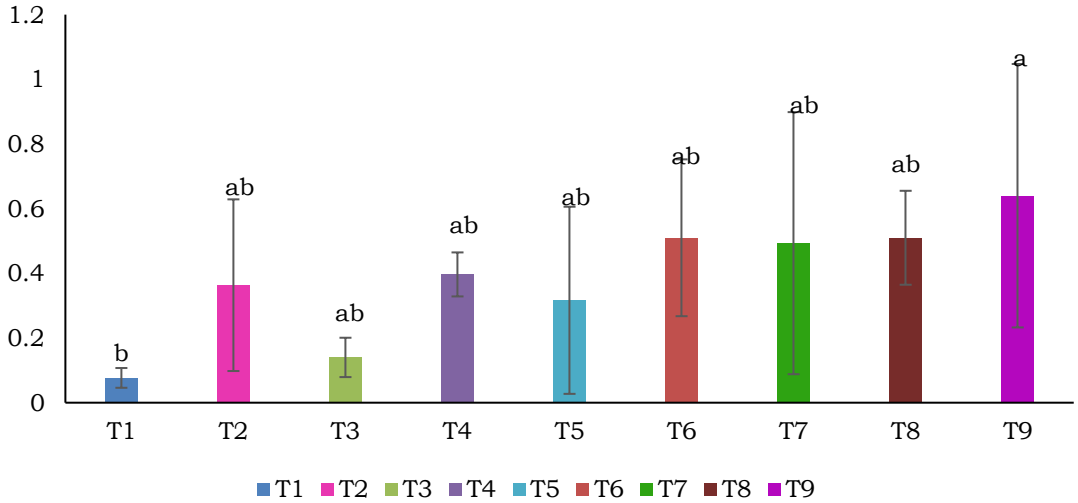



Fig 5. Response of Green Yield at various treatments as affected by vermicompost application. A one-way ANOVA was conducted, followed by Tukey's post hoc test, to assess whether green yield differed significantly among the treatments. Significant differences between treatments are shown by different letters above the bars ($p < 0.05$).

The effect of different treatments on beetroot root yield was found to be statistically significant ($p < 0.05$), as the highest beetroot yield (9.4 t ha$^{-1}$) was recorded with treatment T9 (100% NPKS ha$^{-1}$ + 10 t ha$^{-1}$ VC), where maximum doses of vermicompost were used. This treatment showed a significantly higher yield compared with the control ($T_1$), while being statistically similar to $T_8$ (7.87 t ha$^{-1}$) and $T_6$ (6.17 t ha$^{-1}$). The control ($T_1$), which did not receive any organic or inorganic amendments, had the lowest root yield (0.90 t ha$^{-1}$). This is in agreement with other research showing that the integration of organic and inorganic nutrients enhances soil health, nutrient availability, and the sustainability of the yield (Kumar *et al.*, 2014; Joshi *et al.*, 2015). This may be due to the decrease in EC of saline soil, which can be responsible for increasing nutrient availability. These results correspond to those of Khatun *et al.* (2019), who experimented on maize using a combination of vermicompost and cowdung. Their findings show that vermicompost was successful in significantly lowering the soil EC (from 3.94 dS/m to 1.45 dS/m) and that cow dung significantly lowers the soil EC in contrast to other treatments. Liang *et al.* (2005) discovered the same outcome when they used organic fertilizers to recover saline soil. According to Prapagar *et al.* (2012), organic additions were successful in lowering the pH of saline soil. This conclusion is further supported by Kondal *et al.* (2024), who show that organic manure breaks down quickly and releases all the nutrients that enhance soil chemical properties like pH, total N, available P, and organic matter, which promotes early germination. They also propose that a sustainable agricultural system might incorporate a combination of organic and chemical fertilizers to produce vegetables.

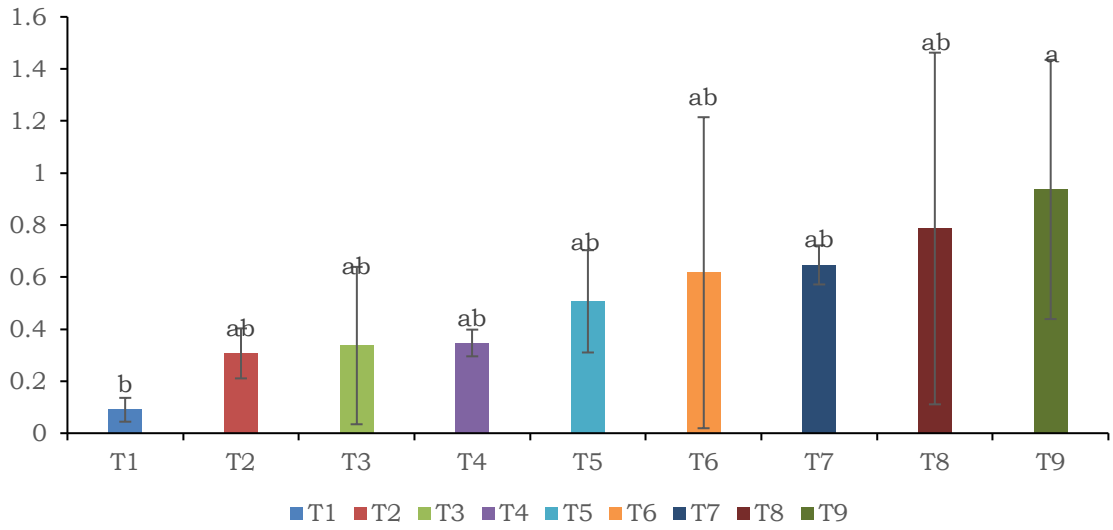



Fig 6. Response of root yield to various treatments affected by vermicompost application. A one-way ANOVA was conducted, followed by Tukey's post hoc test, to assess whether root yield differed significantly among the treatments. Significant differences between treatments are shown by different letters above the bars ($p < 0.05$).

## Conclusion

Vermicompost has a major impact on the physico-chemical characteristics of saline soil and on beetroot yield. The above experimental findings demonstrated that combining 5–10 t ha$^{-1}$ vermicompost with 100% RDF was optimal for beetroot growth and yield. Vermicompost has been proven effective in significantly reducing soil EC (from 2.94 dS/m2 to 0.98 dS/m2) and buffering soil acidity, creating a more suitable environment for nutrient absorption and bringing hope to local farmers. Research has shown that the combined use of inorganic fertilizer and vermicompost significantly improves soil quality and crop productivity under saline conditions. However, further long-term research is needed to evaluate their cumulative effects on soil organic matter dynamics, nutrient cycling, and economic feasibility under varying coastal agro-ecological conditions.

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# Influence of organic and inorganic fertilizers on the morphological growth and yield of broccoli in coastal regions of Bangladesh

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**A B S T R A C T**

A field study was conducted to assess the combined effects of organic and inorganic fertilizers on the growth and yield of broccoli (*Brassica oleracea* var. *italica*) under coastal conditions in Bangladesh, characterized by slightly saline soil (EC 1.67 mS $cm^{-1}$). Six treatment combinations were tested: $T_0$ – Control (no fertilizer application); $T_1$ – 100% recommended dose of inorganic fertilizers (Urea, TSP, MoP); $T_2$ – 100% recommended dose of inorganic fertilizers + 2.5 t $ha^{-1}$ vermicompost; $T_3$ – 100% recommended dose of inorganic fertilizers + 5 t $ha^{-1}$ vermicompost; $T_4$ – 2.5 t $ha^{-1}$ vermicompost; and $T_5$ – 5 t $ha^{-1}$ vermicompost. Results showed that the combined application of 100% RDF with 5 t $ha^{-1}$ vermicompost ($T_3$) significantly improved all vegetative growth parameters, such as plant height, leaf number, leaf length, and leaf diameter, which subsequently enhanced curd diameter, net curd weight, and marketable curd weight, leading to the highest yield per plot. The strongest correlations (r = 0.946) were observed between yield and both net and marketable curd weight, indicating that curd biomass is the most direct determinant of yield. The study concludes that the integration of 100% RDF with 5 t $ha^{-1}$ vermicompost ($T_3$) is the most effective and sustainable nutrient management practice for maximizing broccoli growth and yield under coastal agro-ecological conditions of Bangladesh.

**Keywords:** Broccoli, Vermicompost, Integrated fertilization, Soil nutrient management

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## Introduction

Broccoli (*Brassica oleracea* L. var. *italica*), an important cole crop vegetable belonging to the Brassicaceae (Cruciferae) or mustard family, is gaining popularity in Bangladesh and is known for being a rich source of sulforaphane - a compound with potent anti-carcinogenic properties (Kirsh *et al.*, 2007). In Bangladesh, broccoli is viewed as a promising crop with the potential to thrive in local markets and eventually enter the export sector. Despite this, organic cultivation remains limited in scale. Broccoli is widely recognized as a nutritious and flavorful addition to salads and other health-conscious meals. Broccoli is recognized for its rich composition of vitamins, minerals, dietary fiber, and antioxidants, which play essential roles in promoting overall human health (Cartea *et al.*, 2008; Faller and Fialho, 2009; Porter, 2012). It is a good source of carbohydrates, protein, vitamins A and C, vitamins $B_1$ and $B_2$, calcium, and phosphorus. Compared with cauliflower, broccoli contains approximately 4.0, 2.5, and 2.0 times higher amounts of riboflavin, calcium, and ascorbic acid, respectively

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(Hazra and Som, 2009). Moreover, it has a low glycemic index (GI = 10), making it a suitable and safe vegetable option for individuals with diabetes (Nagraj *et al.*, 2020).

Farmers in Bangladesh have shown growing interest in broccoli cultivation due to its high economic value. The use of balanced and adequate fertilizer combinations is crucial for ensuring the production of high-quality broccoli and attaining maximum yield and profitability (Ahirwar and Nath, 2020). In Bangladesh, many farmers lack awareness of the benefits of balanced fertilization and often cultivate vegetables without following proper fertilizer rates or soil testing. To achieve higher yields, they frequently apply chemical fertilizers indiscriminately while neglecting adequate amounts of organic manure. Such irresponsible fertilizer practices can degrade soil health, reduce produce quality, and shorten shelf life (Mal *et al.*, 2014). Relying solely on chemical fertilizers may boost short-term crop yields, but over time they can harm soil health and crop performance (Gupta *et al.*, 2019). Organic manure can supply essential nutrients to plants, helping maintain crop quality while also enhancing the physical and chemical properties of the soil (Alam *et al.*, 2019). Organic manures can serve as a substitute for synthetic fertilizers (Hossain *et al.*, 2020). The use of locally available manures, such as cow dung and chicken manure, in vegetable cultivation can enhance crop yields while reducing reliance on chemical fertilizers. Additionally, consumers are increasingly seeking high-quality, safer foods and show a strong preference for organic products.

The main objectives of the proposed research are to examine the effects of organic and inorganic fertilizers on the growth and yield performance of broccoli and to determine the optimal level of organic fertilizer application under coastal conditions. Additionally, the study aims to assess the impact of inorganic fertilizers and their combined use on the yield, quality, and economic returns of broccoli.

## Materials and Methods

### *Selection of site*

The study was conducted at the Agricultural Research Field, Noakhali Science and Technology University (NSTU), Noakhali, Bangladesh, located in Agro-Ecological Zone 18 (AEZ-18), which is characterized by normal seasonal flooding and well-drained soils.

### *Selection of test plant material*

A certified high-yielding broccoli variety, Lidia F1, was used for this study, and the seeds were sourced from Siddique Bazar, Dhaka.

### *Land preparation*

The field was thoroughly prepared using a power tiller, followed by harrowing and leveling with a ladder. Individual plots were constructed to a height of 7 cm and a depth of 8 cm, with drainage channels around each plot to prevent lateral runoff from irrigation or rainfall.

### *Crop establishment and management*

Broccoli (*Brassica oleracea* var. *italica*) seedlings were grown in a nursery and later transplanted to the experimental plots at 30 days after sowing when seedlings had 4–5 true leaves. Each plot measured 1.5 m × 1.0 m with a spacing of 50 cm × 50 cm between plants. Uniform agronomic practices, including irrigation, weeding, and pest control, were implemented across all treatments to reduce variation not associated with fertilizer effects.

### *Design of the experiment and treatments*

The experiment followed a Randomized Complete Block Design (RCBD) with three replications. There were eighteen experimental plots. The treatments comprised different combinations of organic and inorganic fertilizers, including:

$T_0$: Control (no fertilizer application)
$T_1$: 100% recommended dose of inorganic fertilizers (Urea, TSP, MoP)
$T_2$: 100% recommended dose of inorganic fertilizers + 2.5 t $ha^{-1}$ vermicompost
$T_3$: 100% recommended dose of inorganic fertilizers + 5 t $ha^{-1}$ vermicompost
$T_4$: 2.5 t $ha^{-1}$ vermicompost

### *Fertilizer application*

Organic fertilizers (vermicompost) were incorporated into the soil one week prior to transplanting. The recommended dose of inorganic fertilizers consisted of Urea, Triple Super Phosphate (TSP), and Muriate of Potash (MoP) at the rates of 37.5, 22.5, and 30.0 g $plot^{-1}$, respectively. Inorganic fertilizers were applied in split doses: nitrogen at half rate, and the full amounts of phosphorus and potassium were incorporated into the soil during final land preparation, while the remaining nitrogen was side-dressed at 30 and 45 days after transplanting.

***Data collection***

Data were collected from three randomly chosen plants per plot to measure plant height (cm), number of leaves, length of leaves (cm), diameter of leaves (cm), curd diameter (cm), net curd weight (g), marketable curd weight (g), and yield per plot (kg plot$^{-1}$).

***Statistical analysis***

All raw data were checked for normality and homoscedasticity (equal variance). The data were compared using one-way ANOVA, and Tukey's post hoc test was applied to identify significant differences among treatments. The data were transformed as required before performing the one-way ANOVA. Microsoft Excel was used to create graphs, while MINITAB 17 was used to perform one-way ANOVA and Tukey's pairwise comparisons.

***Growth parameters as affected by organic and inorganic fertilizer application***

Vegetative growth parameters of broccoli, including plant height, leaf number, leaf length, and leaf diameter, were significantly influenced by different fertilizer treatments. The highest values for all vegetative traits were recorded in $T_3$ (100% RDF + 5 t ha$^{-1}$ vermicompost), whereas the control treatment ($T_0$) showed the lowest performance. The superior growth observed under integrated nutrient management might be attributed to improved nutrient availability, enhanced microbial activity, and better soil physical conditions resulting from vermicompost application. The balanced supply of nutrients from both organic and inorganic sources likely promoted cell division, chlorophyll synthesis, and leaf expansion, ultimately enhancing overall vegetative growth.

## Results and Discussion

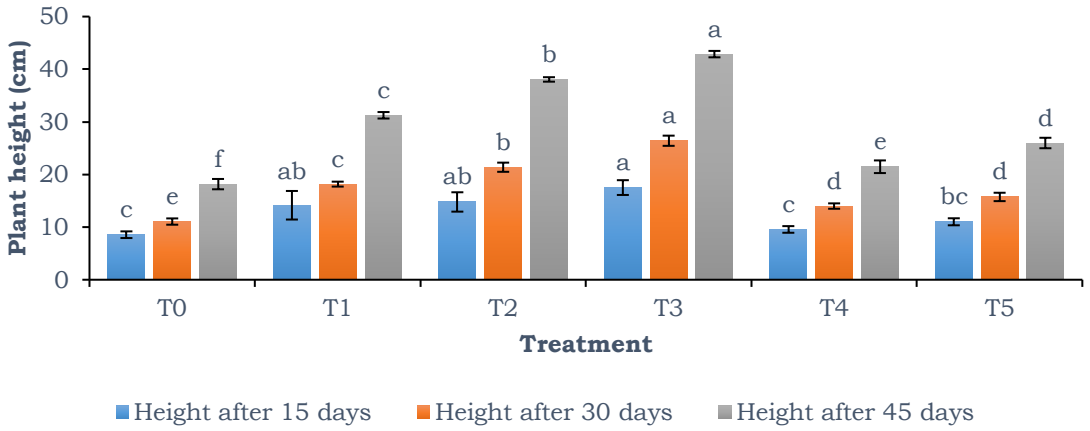



Fig. 1. Plant height after 15, 30 and 45 days as affected by different treatments. Letters above each bar show which treatment groups are statistically different from one another.

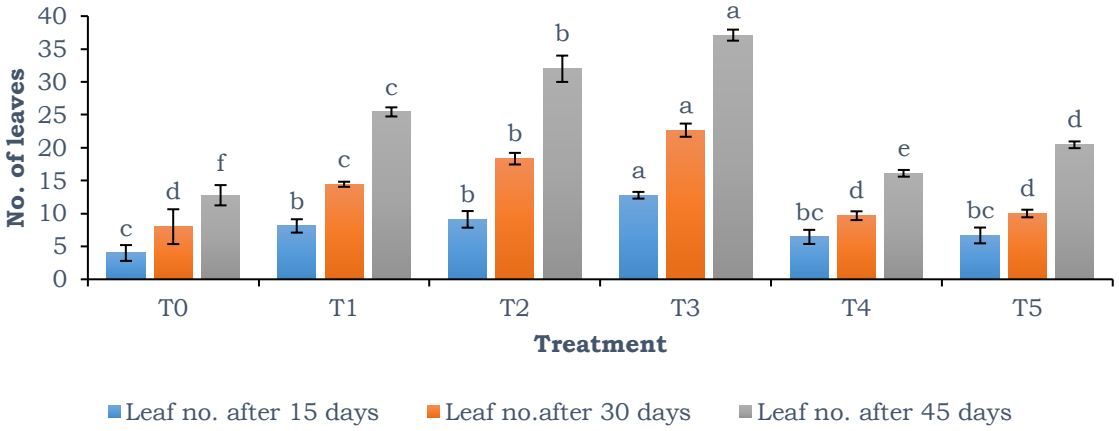



Fig. 2. Leaf number after 15, 30 and 45 days as affected by different treatments. Letters above each bar show which treatment groups are statistically different from one another.

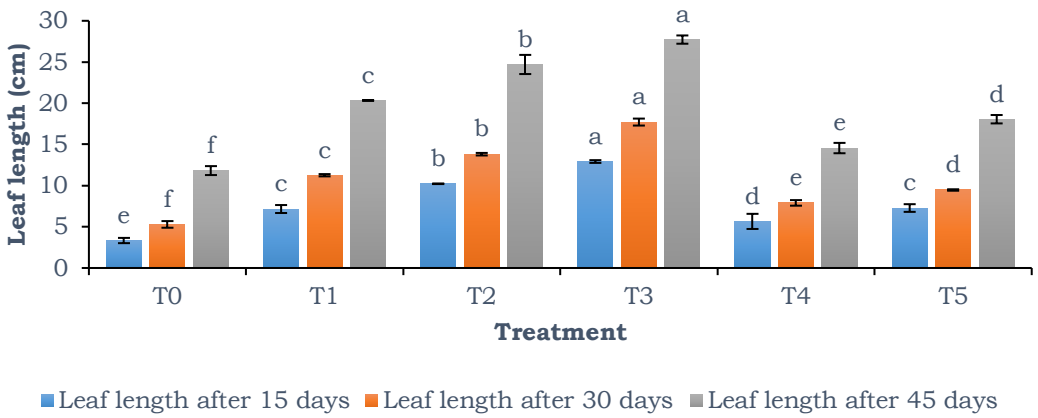



Fig. 3. Leaf length after 15, 30 and 45 days as affected by different treatments. Letters above each bar show which treatment groups are statistically different from one another.

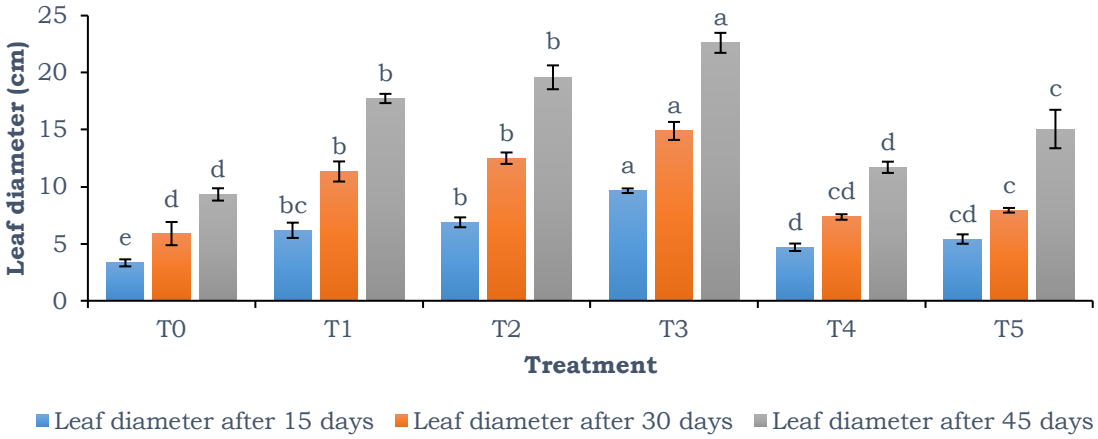



Fig. 4. Leaf diameter after 15, 30 and 45 days as affected by different treatments. Letters above each bar show which treatment groups are statistically different from one another.

*Curd diameter*

The data on curd diameter revealed that the largest curd diameter (10.03 cm) was recorded in the soil treated with $T_3$. This was followed by the $T_2$ treatment, which showed a slightly smaller curd diameter (8.83 cm). In contrast, the smallest curd diameter (5.47 cm) was observed in the soil treated with $T_0$.

These findings indicate that organic and inorganic fertilizer application, particularly the $T_3$ treatment, had a significant positive effect on the development of curd diameter. The influence of different fertilizer treatments on curd diameter is illustrated in Figure 5.

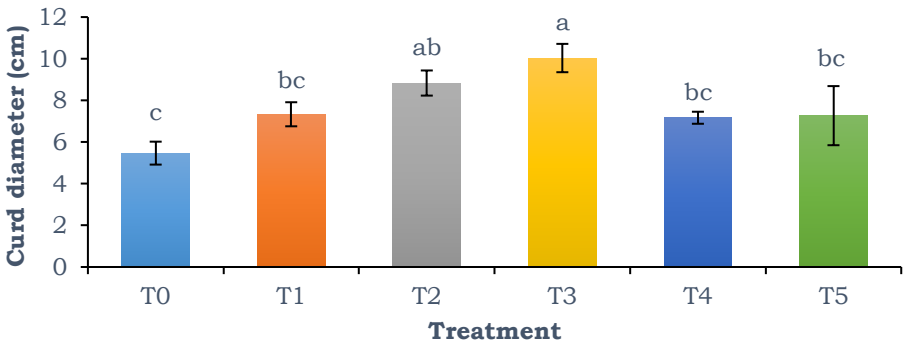



Fig. 5. Curd diameter as affected by different treatments. Letters above each bar show which treatment groups are statistically different from one another.

*Marketable and net curd weight*

Analysis of variance revealed that fertilizer treatments had a significant effect ($p < 0.05$) on both marketable and net curd weights of broccoli. The highest marketable curd weight (430.48 g plant$^{-1}$) was obtained from the $T_3$ treatment, followed by $T_2$ (368.00 g plant$^{-1}$), while the lowest value (206.23 g plant$^{-1}$) was recorded in the control $T_0$. A similar pattern was observed for net curd weight, where $T_3$ produced the maximum trimmed curd weight (374.33 g plant$^{-1}$). The $T_2$ treatment ranked second (320.00 g plant$^{-1}$), whereas $T_0$ recorded the minimum (179.33 g plant$^{-1}$). These results indicate that the integrated application of fertilizers ($T_3$) substantially improved both marketable and edible curd yields compared with individual or no-fertilizer applications. The impacts of different fertilizer treatments on net and marketable curd weights are shown in Figure 6.

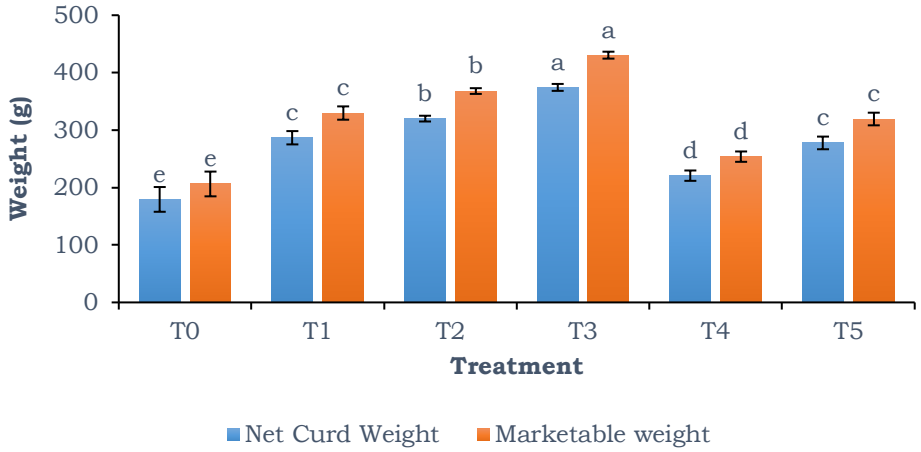



Fig. 6. Net curd weight and marketable curd weight as affected by different treatments. Letters above each bar show which treatment groups are statistically different from one another.

*Yield Plot*[1]

The highest yield (3.5 kg plot$^{-1}$) was obtained from treatment $T_3$, which was statistically similar to $T_2$ and $T_1$, but significantly higher than the control $T_0$ and $T_4$. This result suggests that the fertilizer combination used in $T_3$ provided an optimum nutrient balance that enhanced vegetative growth and curd development. Similar findings were reported by several researchers, who observed that balanced application of organic and inorganic fertilizers improved yield attributes and total yield of broccoli. The lower yield in the control plot may be attributed to soil nutrient deficiency, which restricted plant growth and curd formation. Overall, the positive response of yield to increased fertilizer application up to $T_3$ indicates that proper nutrient supplementation is essential to achieve maximum yield potential in broccoli under coastal conditions. The impacts of different fertilizer treatments on yield per plot are shown in Figure 7.

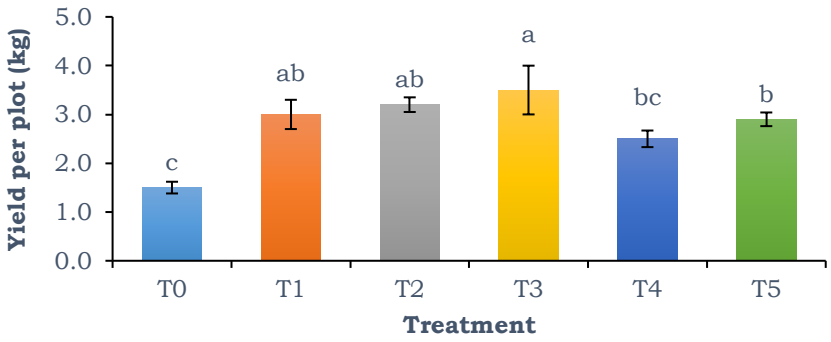



Fig. 7. Yield per plot as affected by different treatments. Letters above each bar show which treatment groups are statistically different from one another.

The results of the current study revealed that both vegetative growth and yield per plot of broccoli increased progressively with higher rates of vermicompost, and the best performance was obtained from the treatment receiving the highest level of vermicompost in combination with the RDF. This finding demonstrates the synergistic impact of organic and inorganic nutrient sources on soil fertility, nutrient uptake, and plant growth in broccoli. The results are in close agreement with those reported by Hasan *et al.* (2024), who observed that increasing vermicompost levels significantly enhanced head yield and quality of broccoli under field conditions. Similarly, the factorial investigation conducted by Mal *et al.* (2014) showed that the highest vermicompost rate (10 t $ha^{-1}$) combined with 100 % RDF produced the maximum curd yield and improved morphological traits. In addition, Meena *et al.* (2017) reported that integrating 75% RDF with higher organic compost levels significantly improved curd weight, plant height, and marketable yield compared with sole inorganic fertilization. The consistency of these results with the current findings strongly supports the conclusion that the combined application of chemical fertilizers and large doses of vermicompost creates an ideal nutrient balance that sustains soil health while maximizing broccoli yield under coastal agro-ecological conditions. Therefore, the present results are fully consistent with previous research, confirming that a high vermicompost rate, together with the recommended inorganic fertilizer dose, yields the most favorable outcome for broccoli production.

***Relationship between morphological traits and the yield of broccoli***

Vegetative characteristics of broccoli (*Brassica oleracea* L. var. *italica*) and yield per plot were tested for relationships. A Spearman correlation analysis was conducted to examine the relationships among these traits (Table 1). Significant correlations with r ≥ 0.5 were considered for further discussion. Statistical significance was assessed by considering p-values ≤0.05.

Table 1. Correlation coefficient (r) of growth parameters and yield of broccoli.

| Properties | Height | Leaf number | Leaf length | Leaf diameter | Curd diameter | Net curd weight | Marketable curd weight |
|---|---|---|---|---|---|---|---|
| Leaf number | 0.998*** | | | | | | |
| Leaf length | 0.994*** | 0.992*** | | | | | |
| Leaf diameter | 0.997*** | 0.992*** | 0.990*** | | | | |
| Curd diameter | 0.953** | 0.959** | 0.975** | 0.948** | | | |
| Net curd weight | 0.977** | 0.967** | 0.988*** | 0.983*** | 0.954** | | |
| Marketable curd weight | 0.977** | 0.967** | 0.988*** | 0.983*** | 0.954** | 1.000*** | |
| Yield per plot | 0.891* | 0.874* | 0.914* | 0.912* | 0.911* | 0.946** | 0.946** |

****, **, * Marked correlations are significant at P≤0.001, 0.01 and 0.05, respectively.*

The correlation matrix demonstrates strong and significant positive associations among the vegetative growth traits and curd-related parameters. For instance, plant height correlates almost perfectly with leaf number (r = 0.998***), leaf length (r = 0.994***), and leaf diameter (r = 0.997***), indicating that increased vertical growth is tightly linked with enhanced leaf productivity. These vegetative attributes also show very high intercorrelations (r > 0.99***), underscoring that canopy development is a coordinated process. The close relationships between growth traits and curd traits (e.g., leaf length vs net curd weight r = 0.988***; leaf diameter vs marketable curd weight r = 0.983***) suggest that improved foliage structure likely supports assimilate partitioning into the curd.

Yield per plot also exhibits significant positive correlations with all growth and curd parameters (e.g., r = 0.946** with net curd weight / marketable curd weight), and somewhat lower but still significant correlations with height (r = 0.891*) and leaf number (r = 0.874*). This implies that although basic vegetative growth contributes to yield, the mass and quality of curd formation are more directly influential for final yield. These findings are consistent with prior studies in broccoli showing that stronger vegetative growth often leads to higher curd yield (e.g., in nitrogen response trials) (Giri *et al.*, 2013).

## Conclusions

The present study clearly demonstrated that the combined application of organic and inorganic fertilizers had a pronounced influence on the growth and yield performance of broccoli. Among the different treatments, the combination containing 100% (RDF) along with the highest level of vermicompost resulted in superior vegetative growth and maximum curd yield. This integrated nutrient management approach enhanced plant height, leaf production, and curd development more effectively than sole or lower-dose applications, indicating improved nutrient availability and uptake efficiency.

Correlation analysis further revealed that broccoli yield was strongly and positively associated with major growth attributes and curd-related parameters. The strongest correlations ($r > 0.946$) were observed between yield and both net and marketable curd weight, suggesting that curd mass is the most direct determinant of overall productivity. These findings confirm that vigorous vegetative growth supports better curd development, ultimately enhancing yield. Therefore, the integration of 100% RDF with vermicompost can be recommended as an effective and sustainable nutrient management practice to maximize broccoli production under the coastal conditions of Bangladesh.

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# Evaluation of soil fertility status at the Agricultural Service Training Center (ASTC) Research Farm, Kuru, Jos South LGA, Plateau State, Nigeria

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**A B S T R A C T**

This study evaluated the soil fertility status of the Agricultural Service Training Centre (ASTC) Research Farm in Kuru, Jos South LGA, Plateau State, Nigeria. Specifically, the study assessed the soil fertility status and identified nutrient deficiencies in the area. Soil samples were collected at various depths (0-20 cm and 20-50 cm) from seven augering points and analysed for physical and chemical properties, including pH, electrical conductivity, organic matter, organic carbon, total nitrogen, exchangeable cations, extractable phosphorus, and sulphur. The results revealed that the soil has a slightly acidic to neutral pH, low organic matter and organic carbon content, moderate to high cation exchange capacity, and varying levels of extractable phosphorus and sulphur. These findings suggest potential limitations in soil fertility and ecosystem services that may affect crop growth and productivity. Based on the study's findings, recommendations are made for farmers and land managers to improve soil health and productivity, including adding organic matter, applying phosphorus fertilizers as needed, using conservation practices, conducting regular soil testing, selecting suitable crops, and planning rotations. Furthermore, land managers are advised to develop tailored nutrient management strategies, promote sustainable agricultural practices, and provide farmers with training and resources on soil testing, fertilizer application, and crop selection.

**Keywords:** Soil fertility, Nutrient deficiencies, Soil health, Sustainable agriculture, Nutrient management

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## Introduction

The Agricultural Service Training Center (ASTC) Research Farm in Jos South, Nigeria, is a vital institution for agricultural research and development (Momoh *et al.*, 2018). The farm is a hub for innovation and knowledge sharing, promoting sustainable agriculture and enhancing crop yields (Agada, 2021). However, like many farmlands in Nigeria, the farm's soil fertility status is likely influenced by various factors, including management practices, fertilizer application, and soil degradation (Hjelm and Dasori, 2012). The ASTC Research Farm serves as a critical testing ground for new agricultural techniques aimed at addressing the challenges posed by soil degradation and nutrient depletion (Momoh *et al.*, 2018; Agada, 2021).

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Through rigorous experimentation and field trials, researchers at the farm assess the effectiveness of various fertilization strategies and crop rotation systems for restoring and maintaining soil health (Srivastava *et al.*, 2024). According to Ţopa *et al.* (2025), sustainable practices such as crop rotation, conservation agriculture, and the use of organic amendments can restore soil structure, increase organic matter, and promote biodiversity, ultimately enhancing soil health. Emphasizing sustainable practices, the farm integrates organic amendments and conservation tillage methods to reduce erosion and improve soil structure (Seitz *et al.*, 2019). Moreover, extension services provided by ASTC facilitate the transfer of innovative technologies to local farmers, empowering them to optimize input use and increase productivity while safeguarding the environment (Raji *et al.*, 2024). In this way, the farm contributes to advancing scientific knowledge and plays a transformative role in promoting food security and rural livelihoods in Jos South and beyond (Guluwa and Jimmy, 2018).

Soil is a multifaceted system of minerals, soil organic matter (SOM), water, and air. Soil quality, encompassing interactive physical, chemical, and biological properties, determines its suitability for agriculture and other uses. Soil fertility encompasses both the chemical and physical properties of soil (Loss *et al.*, 2014). Soil fertility assessment estimates the availability of native and residual nutrients for crop growth and determines fertilizer requirements for profitable yields (Nafiu *et al.*, 2012). Soil texture, structure, and colour are essential physical parameters of soil. Similarly, soil reaction (pH), organic matter, and macro and micronutrients are important soil chemical parameters. These properties play significant roles in soil fertility and testing.

Assessing soil fertility is vital for informed fertilizer application and soil management (Singh *et al.*, 2024). By analyzing nutrient content, pH, and other physical and chemical properties, farmers and researchers can detect deficiencies, optimize fertilizer use, and promote sustainable practices (Nakachew *et al.*, 2024). This approach not only enhances crop productivity but also reduces the environmental impact of agricultural activities (Srivastava *et al.*, 2024). Moreover, regular soil fertility assessments provide a dynamic understanding of soil health over time, enabling timely adjustments to cultivation practices (Ţopa *et al.*, 2025). This proactive approach is essential in adapting to changing climatic conditions and mitigating the risks of soil degradation (Al-Shammary *et al.*, 2024). By integrating soil testing data with site-specific crop requirements, farmers can tailor nutrient applications, avoid over-fertilization, and minimize runoff that contributes to water pollution (Srivastava *et al.*, 2024). Furthermore, advancements in soil analysis techniques, including precision agriculture tools and remote sensing, have enhanced the accuracy and accessibility of fertility assessments (Al-Shammary *et al.*, 2024).

Soil properties exhibit geographic and chronological variability influenced by inherent factors such as soil formation, management practices, fertilization, and crop rotation (Sharma *et al.*, 2011). The high degree of variability in soil features due to anthropogenic activities requires monitoring key indicators and their critical limits to assess changes in soil quality for different agro-ecological zones at local, national, and global levels (Yakubu and Mallo, 2019). Many soil indicators interact with each other; thus, the value of one is affected by one or more of the other parameters (Arshad and Martin, 2002). Soil is a crucial natural resource, and its nutrients play a vital role in ensuring food security, promoting human health, and fostering sustainable development. Soil fertility and nutrient management are essential in modern agriculture and play a crucial role in sustainable development and the management of fertilizers at specific crop production sites (Harishma *et al.*, 2025). Therefore, assessment of soil fertility is imperative as a decision-making tool for the sustainable management of soil nutrients. Fertility management based on soil testing is an effective tool for increasing agricultural soil production. Analysing soil nutrient content, spatial distribution, and the classification of soil nutrient levels are essential for developing scientifically and economically sound fertilization recommendations, thereby reducing excessive fertilizer application.

Ultimately, these practices contribute to the resilience and sustainability of agricultural systems, promoting long-term food security while preserving ecosystem balance (FAO,

2017). However, in Nigeria, the indiscriminate application of fertilizers by farmers, without considering the specific nutrient needs of the soil and crops, has led to inefficient use, resulting in low soil fertility and reduced crop productivity. Similarly, at the Agricultural Service Training Center (ASTC) Research Farm, there is a significant lack of comprehensive data regarding the soil fertility status. This data deficiency poses a challenge to informed decision-making regarding fertilizer application and soil management practices, potentially leading to inefficient resource use, reduced crop yields, and environmental degradation. Accurate soil fertility data is essential for developing tailored fertilization strategies that optimize agricultural productivity while minimizing adverse environmental impacts. Without this information, there is a risk of over-application or under-application of fertilizers, leading to nutrient imbalances and diminished soil health. Addressing this knowledge gap is crucial for ensuring effective fertilizer use and sustainable soil management, supporting both agricultural output and environmental stewardship.

This study aims to address this knowledge gap by evaluating the soil fertility status of the ASTC Research Farm, providing essential data to inform sustainable soil management practices and optimize crop productivity. By assessing the soil's physical and chemical properties, identifying nutrient deficiencies and limitations, and providing recommendations for sustainable soil management practices, this study will contribute to improved agricultural productivity and sustainability. Addressing this knowledge gap is paramount for ensuring the effective use of fertilizers and the sustainable management of soil resources, thereby supporting both agricultural output and environmental stewardship.

The specific objectives of this study are to:

i. assess the soil fertility status of the Agricultural Service Training Center (ASTC) Research Farm in Jos South Local Government Area.
ii. identify the nutrient deficiencies and limitations in the soil within the study area.

## Materials and Methods

The study was carried out at the Agricultural Service Training Centre (ASTC) Research Farm, Kuru, Jos South Local Government Area, Plateau State, Nigeria. The farm is located at Latitude 9°44'N, Longitude 8°51'E, at an elevation of 1,240 m above sea level [m.a.s.l.]. Jos South LGA has an area of approximately 510 km². The region's climate is largely controlled by its high altitude, with mean annual temperatures ranging between 18°C and 22°C. The soils are ferruginous and loamy, characteristic of the Jos Plateau.

*Materials used*

(i) Munsell soil color chart, (ii) Soil auger, (iii) Sampling bags, (iv) Permanent marker, (v) Weighing balance, (vi) pH meter, (vii) EC meter, (viii) Cylinder, (ix) Beaker, (x) Mortar and pestle, (xi) Stirrer, (xii) Hydrometer, (xiii) Sieve (2mm), (xiv) Stopwatch

A random survey was conducted within the study area to determine the soil color, texture, and consistency using a soil auger. To assess the fertility status of the study area, soil samples were collected using an auger from the soil surface at various depths (0-20 cm and 20-50 cm). The samples were analyzed for physical and chemical properties at the Soil Science Laboratory of FECOLART Kuru-Jos.

The soil samples were analyzed for:

- Electrical Conductivity (EC): Measured using an Electrical Conductivity meter in a soil-water suspension (1:2.5) (Jaiswal, 2003).
- Organic Matter (%): Calculated by multiplying the organic carbon content by a factor of 1.724 (Walkley and Black, 1934).
- Total Nitrogen: Determined using the Micro Kjeldahl method (Bremner and Mulvaney, 1982).
- Exchangeable Cations: Extracted using neutral ammonium acetate ($NH_4OAc$) and determined by flame photometry for calcium and magnesium (Black, 1965).
- Soil pH: Measured potentiometrically in a 1:2.5 soil-water ratio (Moberg, 2000; McLean, 1982).
- Organic Carbon: Determined by the wet digestion method of Walkley-Black (Nelson and Sommer, 1982; Moberg, 2000).

- Available Sulphur: Extracted with 0.15% $CaCl_2$ solution (1:5 ratio), shaken for 30 min, filtered, and determined turbidimetrically with $BaCl_2$ (Tabatabai and Bremner, 1970).
- Extractable Phosphorus: Determined using the Bray-1 method (Bray and Kurtz, 1945; Moberg, 2000) followed by color development with ascorbic acid (Murphy and Riley, 1962).
- Determination of Exchangeable Bases and Cation Exchange Capacity: Cation exchange capacity was determined by the ammonium acetate saturation method (Chapman, 1965).

## Results and Discussion

Table 1. Textural properties of the seven (7) mapping units.

| Sample No | Soil color | | Sand | Silt | Clay | Textural class |
|---|---|---|---|---|---|---|
| | Dry | Moist | | | | |
| | | ***0-20 cm*** | | | | |
| C1a | 10YR 6/8 Brown yellow | 10YR 5/8 Yellowish brown | 41.4 | 16.28 | 42.32 | Clay |
| C2a | 10YR 6/8 Brown yellow | 10YR 5/8 Yellowish brown | 44.4 | 16.28 | 39.32 | Clay loam |
| C3a | 10YR 6/8 Brown yellow | 10YR 5/8 Yellowish brown | 43.4 | 18.28 | 38.32 | Clay loam |
| C4a | 10YR 6/8 Brown yellow | 10YR 5/8 Yellowish brown | 54.4 | 19.60 | 26.00 | Sandy clay loam |
| C5a | 10YR 6/8 Brown yellow | 10YR 5/8 Yellowish brown | 47.4 | 19.28 | 33.32 | Sandy clay loam |
| C6a | 10YR 6/8 Brown yellow | 10YR 5/8 Yellowish brown | 45.4 | 21.28 | 33.32 | Sandy clay loam |
| C7a | 10YR 6/8 Brown yellow | 10YR 5/8 Yellowish brown | 41.4 | 23.28 | 33.32 | Clay loam |
| | | ***20-50 cm*** | | | | |
| C1b | 10YR 6/8 Brown yellow | 10YR 5/8 Yellowish brown | 47.4 | 16.28 | 36.32 | Sandy clay |
| C2b | 10YR 6/8 Brown yellow | 10YR 5/8 Yellowish brown | 47.4 | 17.28 | 35.32 | Sandy clay |
| C3b | 10YR 6/8 Brown yellow | 10YR 5/8 Yellowish brown | 46.4 | 16.28 | 37.32 | Sandy clay |
| C4b | 10YR 6/8 Brown yellow | 10YR 5/8 Yellowish brown | 45.4 | 12.28 | 42.32 | Sandy clay |
| C5b | 10YR 6/8 Brown yellow | 10YR 5/8 Yellowish brown | 42.4 | 15.28 | 42.32 | Clay |
| C6b | 10YR 6/8 Brown yellow | 10YR 5/8 Yellowish brown | 43.4 | 21.28 | 35.32 | Clay loam |
| C7b | 10YR 6/8 Brown yellow | 10YR 5/8 Yellowish brown | 40.4 | 21.28 | 38.32 | Clay loam |

*Source: Field Survey, 2025*

The laboratory analysis revealed that the soil samples exhibited textural classes of clay, sandy clay, clay loam, and sandy clay loam at both the surface (0-20 cm) and sub-surface (20-50 cm) depths. These findings are consistent with those of Yusuf *et al.* (2015), who observed similar soil textures across different land-use types. The implications of these findings are significant, as understanding soil texture is crucial for informed decisions about crop selection, soil management, and land-use planning. Specifically, the presence of clay, sandy clay, clay loam, and sandy clay loam soils necessitates tailored strategies for water and nutrient management. Effective soil structure management and nutrient application can optimize crop productivity while minimizing environmental impact. Moreover, these insights can inform land suitability assessments and soil conservation efforts, ultimately contributing to more sustainable agricultural practices.

As noted by Brady and Weil (2002), soils with predominantly large particles tend to drain quickly and have lower fertility, whereas very fine-textured soils may be poorly drained and prone to waterlogging, rendering them less suitable for agriculture.

Differences in texture can significantly affect the soil's physical and chemical properties. Given the composition of sand, clay, and silt in the soil within the project area, along with other parameters such as organic matter content, moisture content, and pH, the soil is versatile, productive, and capable of supporting microbial growth and plant life. The relatively permanent nature of these characteristics makes them useful for comparing the abilities of different soils and evaluating their suitability for specific uses.

Table 2. Chemical properties of the seven (7) mapping units.

| Sample No | pH $h_2o$ | pH $cacl_2$ | EC ppm | OM (%) | K+ ppm | Mineral N (mg $kg^{-1}$) | Phosphorus ppm | Sulphur Ppm | Organic carbon |
|---|---|---|---|---|---|---|---|---|---|
| ***0-20 cm*** | | | | | | | | | |
| C1a | 6.58 | 5.95 | 49 | 0.29 | 0.0026 | 17.85 | 0.14 | 1.48 | 0.12 |
| C2a | 6.64 | 5.33 | 47 | 0.29 | 0.0025 | 16.05 | 0.08 | 1.18 | 0.16 |
| C3a | 6.70 | 5.11 | 64 | 0.28 | 0.0044 | 18.98 | 0.00 | 1.56 | 0.11 |
| C4a | 6.71 | 5.32 | 73 | 0.28 | 0.0049 | 17.85 | 0.08 | 1.32 | 0.09 |
| C5a | 6.56 | 5.16 | 60 | 0.29 | 0.0039 | 18.53 | 0.10 | 0.90 | 0.10 |
| C6a | 6.38 | 4.98 | 89 | 0.28 | 0.0043 | 17.18 | 0.05 | 1.24 | 0.11 |
| C7a | 6.45 | 4.03 | 158 | 0.29 | 0.0057 | 27.12 | 0.00 | 1.11 | 0.18 |
| Mean | 6.57 | 5.13 | 77.14 | 0.29 | 0.0040 | 19.08 | 0.06 | 1.26 | 0.12 |
| ***20-50 cm*** | | | | | | | | | |
| C1b | 6.80 | 5.44 | 82 | 0.27 | 0.0050 | 19.44 | 0.17 | 1.65 | 0.19 |
| C2b | 6.71 | 5.21 | 49 | 0.27 | 0.0038 | 15.82 | 0.12 | 1.33 | 0.10 |
| C3b | 6.83 | 5.29 | 45 | 0.28 | 0.0032 | 16.95 | 0.20 | 1.51 | 0.19 |
| C4b | 6.79 | 5.15 | 34 | 0.27 | 0.0043 | 16.49 | 0.00 | 0.89 | 0.14 |
| C5b | 6.88 | 5.73 | 53 | 0.29 | 0.0029 | 15.37 | 0.09 | 1.03 | 0.21 |
| C6b | 6.75 | 4.17 | 25 | 0.28 | 0.0027 | 17.85 | 0.08 | 1.02 | 0.11 |
| C7b | 6.91 | 4.26 | 48 | 0.28 | 0.0039 | 19.89 | 0.06 | 1.06 | 0.15 |
| Mean | 6.81 | 5.04 | 48 | 0.28 | 0.0033 | 17.40 | 0.09 | 1.36 | 0.16 |

*Source: Field Survey, 2025*
*Note: Mineral N refers to extractable $NO_3^-$-N + $NH_4^+$-N.*

Table 2 presents the chemical properties of the seven mapping units, including pH, electrical conductivity (EC), organic matter (OM), potassium ($K^+$), mineral nitrogen (N), phosphorus (P), sulphur (S), and organic carbon (OC) content. These parameters are essential for understanding soil fertility and nutrient availability.

### *Soil pH*

The soil pH ranged from 6.38 to 6.91, indicating slightly acidic to neutral conditions. This range is considered ideal for most crops, as it allows for optimal nutrient availability. According to Jackson *et al.* (2018), this pH range supports the availability of essential nutrients like N, P, K, S, Ca, Mg, B, Cu, Fe, and Zn. The finding implies that the soil is suitable for a wide range of crops, and the optimal pH range may reduce the need for lime or other pH-adjusting amendments.

### *Mineral nitrogen content*

Mineral nitrogen ranged from 15.37 to 27.12 mg $kg^{-1}$ across depths, with a mean of 19.08 mg $kg^{-1}$ in the 0–20 cm layer and 17.40 mg $kg^{-1}$ in the 20–50 cm layer. These values are low for arable soils in the tropics, where >40 mg $kg^{-1}$ is often considered adequate for crop uptake during the growing season (Weil and Brady, 2016). The low mineral N likely reflects low organic matter content and limited organic inputs at the site. The slightly higher values in the topsoil compared to the subsoil are consistent with the expected pattern, driven by greater organic matter and microbial activity near the surface. This suggests that nitrogen fertilization or legume-based rotations will be necessary to meet crop demand and prevent yield limitations.

### *Organic matter and organic carbon content*

Organic matter content ranged from 0.27% to 0.29%, and organic carbon from 0.12% to 0.16%. Both are considered very low (Brady and Weil, 2002), indicating potential limitations to soil fertility, structure, and water-holding capacity. Low organic matter can result from intensive tillage, inadequate crop rotation, or insufficient organic amendments (Wang *et al.*, 2020; Pittarello *et al.*, 2021). Strategies such as incorporating cover crops or organic amendments may be necessary to enhance soil health.

***Exchangeable potassium content***

Exchangeable $K^+$ ranged from 0.0025 to 0.0057 ppm, indicating very low levels. According to Landon (2014), values <0.2 cmolc $kg^{-1}$ are considered low for most crops. This suggests a high likelihood of potassium deficiency and the need for K fertilization (Zhang *et al.*, 2013).

***Extractable phosphorus and sulphur content***

Extractable phosphorus ranged from 0.06 to 0.09 ppm, indicating low to moderate levels of available P, while sulphur ranged from 1.26 to 1.36 ppm, indicating moderate to adequate levels. The low to moderate phosphorus content may limit crop growth and productivity, while the moderate to adequate sulphur content suggests sulphur deficiency is unlikely to be a major concern. Knowledge of these parameters enables farmers and land managers to develop targeted plans to enhance soil fertility, structure, and ecosystem services, ultimately improving crop productivity and sustainability (Yusuf *et al.*, 2015).

## Conclusion

This study assessed the soil fertility status of the Agricultural Service Training Center (ASTC) Research Farm in Jos South Local Government Area. The results revealed that the soil has a slightly acidic to neutral pH, low organic matter and organic carbon content, moderate to high cation exchange capacity, and varying levels of extractable phosphorus and sulphur. These findings suggest that the soil has potential limitations to soil fertility and ecosystem services, which may impact crop growth and productivity.

## Recommendations

Based on the study's findings, the following recommendations are made:

- Farmers at ASTC Research Farm should apply organic amendments and phosphorus fertilizers where soil tests indicate deficiencies, adopt conservation practices such as reduced tillage and crop rotation, and match crop selection to current soil nutrient status to improve soil health and productivity.
- Extension personnel should provide on-farm support for regular soil testing, interpret results for farmers, and deliver practical training on balanced fertilization, crop rotation planning, and conservation practices tailored to local soil conditions.
- Land policy managers should develop nutrient management guidelines based on soil cation exchange capacity and nutrient levels, promote incentives for sustainable practices like cover cropping and reduced tillage, and strengthen farmer access to soil testing services and training programs.

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# Status and distribution of available sulphur in tea-growing soils of Bangladesh

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**A B S T R A C T**

This study assessed the distribution and fertility status of available sulphur in tea-growing soils of Bangladesh using 132 paired soil samples collected from 13 tea estates at depths of 0-23 cm and 23-46 cm. Available sulphur was determined using a 0.15% calcium chloride extraction, followed by turbidimetric measurement of barium sulphate. Surface soils contained 0.12 to 69.13 mg/kg available sulphur and sub-surface soils contained 0.58 to 61.00 mg/kg, with mean values of 15.61 and 15.47 mg/kg, respectively. Based on critical limits, 44.70% of surface samples and 47.73% of sub-surface samples were in the low category, indicating a widespread risk of sulphur deficiency. Marked estate-wise variation was observed. Bilashcherra Experimental Farm, Karnafuli, Kazi and Kazi, and Karotoa showed comparatively high mean values, whereas Allynugger, Malnicherra, BTRI Farm, and Sathgao remained in the low range. Available sulphur was positively associated with soil pH and organic matter at both depths, and the relationship with organic matter was strongest in the sub-surface layer. Mean sulphur concentration did not differ significantly between the two depths, but the wide within-estate and between-estate variation indicated that blanket fertilizer recommendations would be inefficient. The study provides a baseline for site-specific sulphur management in Bangladesh tea soils.

**Keywords:** Available sulphur, Tea soil, Soil fertility, Bangladesh, Organic matter

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## Introduction

Tea [*Camellia sinensis* (L.) O. Kuntze] is an economically important plantation crop in Bangladesh and continues to contribute to employment, rural livelihoods, and the agro-based economy. Tea cultivation in Bangladesh is concentrated mainly in the established tea-growing regions of Sylhet, Chattogram, and the newer northern tea areas, where soil fertility management remains important because nutrient status varies considerably among locations and estates (Boonerjee *et al.*, 2025; Sadi *et al.*, 2025; Zohora and Biswas, 2025).

Sulphur is an essential secondary macronutrient required for normal plant growth and development. It is involved in the synthesis of sulphur-containing amino acids, proteins, vitamins, enzymes, and other important metabolites, and an inadequate sulphur supply can reduce plant growth and yield. In tea plantations, recent work has further emphasized that available sulphur is an important component of nutrient cycling and should receive greater attention in nutrient management (Narayan *et al.*, 2023; Wang *et al.*, 2025a).

The availability of sulphur in soil is influenced by several interacting factors, especially soil pH, organic matter, and fertilization history. Soil pH can strongly affect nutrient transformation and uptake, as well as tea plant performance, while fertilization strategies can alter rhizosphere soil conditions and tea plant quality. Recent broader analyses of tea plantations have also shown that many tea-growing soils are affected by acidification, nutrient deficiencies, and nutrient imbalances, which together can influence nutrient availability and overall soil fertility (Jia *et al.*, 2024; Miao *et al.*, 2024; Wang *et al.*, 2025b).

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In Bangladesh, recent studies have reported acidic soil conditions and variable nutrient status in tea-growing areas, and field surveys have documented visible nutrient deficiency symptoms in commercial tea estates. However, detailed information on the distribution and fertility status of available sulphur in tea-growing soils of Bangladesh remains limited, particularly with respect to estate-wise variation, depth-wise comparisons, and its relationship with soil pH and organic matter. Therefore, the present study was undertaken to determine the available sulphur content of tea-growing soils of Bangladesh, classify soil samples into fertility categories, compare sulphur status between surface and sub-surface soils, and examine the relationship of available sulphur with soil pH and organic matter (Sadi *et al.*, 2025; Zohora and Biswas, 2025).

## Materials and Methods

### *Study area*

The study was based on 132 sampling locations from 13 tea estates situated in the major tea-growing districts of Bangladesh, namely Moulvibazar, Sylhet, Chattogram, and Panchagarh. At each location, soil samples were collected from two depths: surface soil (0–23 cm) and sub-surface soil (23–46 cm), giving a total of 264 soil samples. The selected estates represented different physiographic settings, plantation ages, and management conditions, allowing comparison of sulphur status across a broad range of tea-growing environments.

### *Soil analysis*

Soil pH was determined in a 1:2.5 soil: water suspension using the method described by Jackson (1973). Soil organic carbon was determined by the Walkley and Black wet oxidation method, and soil organic matter was estimated from the organic carbon content following the conventional conversion procedure (Walkley and Black, 1934). Available sulphur was extracted with 0.15% calcium chloride and determined turbidimetrically as barium sulphate, following Williams and Steinbergs (1959); turbidity was measured spectrophotometrically at 420 nm.

### *Statistical analysis*

Data were entered and organized in Microsoft Excel (Microsoft 365, Microsoft Corporation, Redmond, WA, USA), and statistical analyses were performed using Minitab 21. Descriptive statistics were computed for each tea estate and for the complete dataset, including sample size, mean, minimum, maximum, median, and standard deviation. Based on available sulphur concentration, soil samples were classified as low (<10 mg/kg), medium (10–20 mg/kg), and high (>20 mg/kg). Pearson's correlation coefficient was used to examine the relationships of available sulphur with soil pH and organic matter content. A paired t-test was used to compare the mean sulphur concentration between surface and sub-surface soils. Statistical significance was assessed at the 5% probability level.

## Results and Discussion

### *Overall sulphur status*

Available sulphur in surface soils ranged from 0.12 to 69.13 mg/kg, with a mean of 15.61 mg/kg and a median of 15.00 mg/kg. In sub-surface soils, available sulphur ranged from 0.58 to 61.00 mg/kg, with a mean of 15.47 mg/kg and a median of 11.61 mg/kg. The paired comparison showed no significant difference in overall mean sulphur concentration between the two depths ($p = 0.861$). The wide range of values at both depths indicated marked spatial heterogeneity in sulphur availability across tea-growing soils. This variation likely reflects differences among estates in soil condition, organic matter status, topographic position, drainage, leaching intensity, and fertilizer management. Therefore, the results support estate-specific rather than blanket sulphur management. A recent study in tea soils of Lalmonirhat, Bangladesh, also reported available sulphur in the low-to-moderate range, although with a narrower range than observed in the present multi-estate dataset (Sadi *et al.*, 2025). Broader recent tea-soil analyses likewise show strong spatial variation in nutrient status and pH across tea plantations, driven by the combined influence of climate, location, soil type, elevation, and management (Sadi *et al.*, 2025; Wang *et al.*, 2025b).

Table 1. Estate-wise statistics of available sulphur in surface soils (0-23 cm) of tea estates in Bangladesh.

| Tea Estate | No. of samples | Mean (mg/kg) | Minimum (mg/kg) | Maximum (mg/kg) | SD |
|---|---|---|---|---|---|
| Bilashcherra Experimental Farm | 21 | 30.19 | 25.00 | 44.00 | 4.76 |
| Karnafuli | 8 | 25.64 | 10.74 | 41.04 | 10.49 |
| Kazi & Kazi | 14 | 23.14 | 12.00 | 31.00 | 6.00 |
| Karotoa | 9 | 21.33 | 15.00 | 29.00 | 4.87 |
| Neptune | 10 | 15.67 | 2.44 | 33.66 | 10.89 |
| Oodaleah | 9 | 13.77 | 2.78 | 69.13 | 21.12 |
| Patrakhola | 5 | 10.05 | 3.87 | 18.46 | 5.69 |
| Rajghat | 9 | 9.68 | 1.52 | 24.44 | 8.88 |
| Sathgao | 10 | 8.75 | 1.18 | 24.85 | 9.28 |
| Jagcherra | 11 | 7.99 | 0.80 | 36.85 | 11.02 |
| BTRI Farm | 5 | 5.52 | 0.29 | 15.84 | 6.16 |
| Malnicherra | 10 | 4.55 | 0.74 | 7.84 | 2.21 |
| Allynugger | 11 | 3.53 | 0.12 | 11.08 | 3.33 |

***Surface soil sulphur distribution***

Surface soil sulphur status varied markedly among estates (Table 1). Bilashcherra Experimental Farm recorded the highest mean surface sulphur concentration (30.19 mg/kg), followed by Karnafuli (25.64 mg/kg), Kazi and Kazi (23.14 mg/kg), and Karotoa (21.33 mg/kg). In contrast, Allynugger (3.53 mg/kg), Malnicherra (4.55 mg/kg), and BTRI Farm (5.52 mg/kg) recorded the lowest mean values, while Jagcherra (7.99 mg/kg), Sathgao (8.75 mg/kg), and Rajghat (9.68 mg/kg) also remained within the low fertility range. Oodaleah showed the widest spread of surface values, including the highest individual observation in the surface dataset (69.13 mg/kg), which indicated marked within-estate heterogeneity.

The estate-wise mean values are shown in Figure 1. The chart confirms that Bilashcherra Experimental Farm maintained the strongest surface and sub-surface sulphur status, whereas Allynugger, Malnicherra, BTRI Farm, Jagcherra, Sathgao, and Rajghat remained in the low range. Similar heterogeneity in available sulphur between estates has been reported in tea-growing areas of India, where local differences in soil acidity, organic carbon status, and garden-level management produced contrasting sulphur classes among gardens and sub-districts (Ghosh *et al.*, 2006; Malakar *et al.*, 2022).

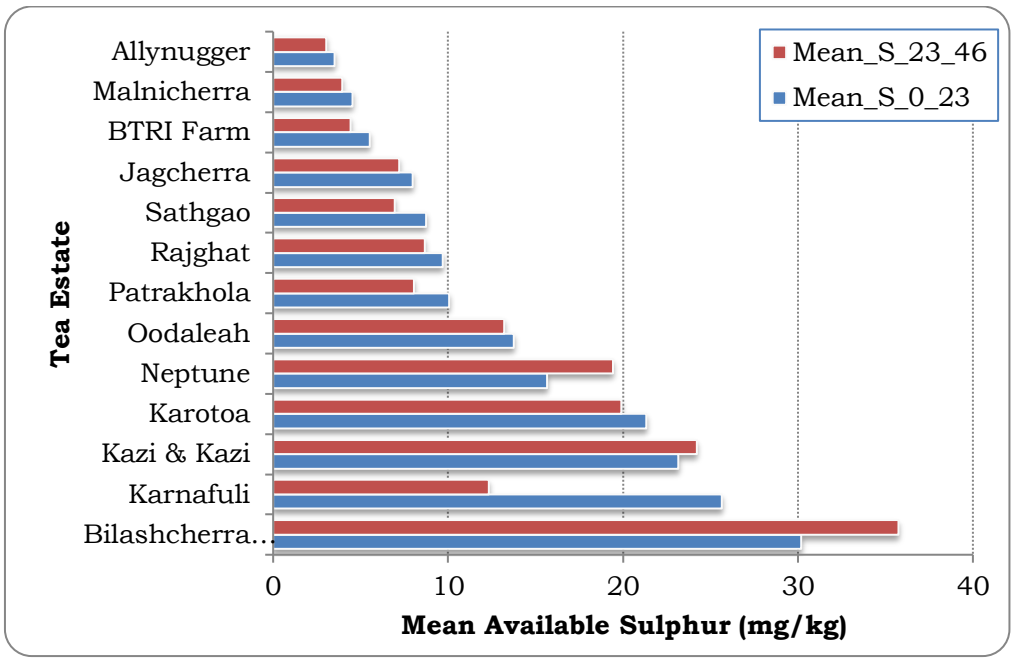



Fig. 1. Mean available sulphur by tea estate at 0-23 cm and 23-46 cm depths.

***Sulphur fertility classes by depth***

Based on the critical limits used in this study, 59 surface samples (44.70%) were low in available sulphur, 23 were medium (17.42%), and 50 were high (37.88%). In the sub-surface layer, 63 samples (47.73%) were low, 27 (20.45%) were medium, and 42 (31.82%) were high (Figure 2). The predominance of low-class samples at both depths indicates that sulphur deficiency is a widespread concern in tea soils. This pattern is agronomically important because plant-available sulphur occurs mainly as sulphate, which is mobile in soil and susceptible to loss, while a large proportion of soil sulphur is associated with organic matter and becomes available only through mineralization. Under acidic, high-rainfall tea-growing environments, inadequate replenishment can therefore lead to sulphur deficiency (Narayan *et al.*, 2023; Wang *et al.*, 2025a).

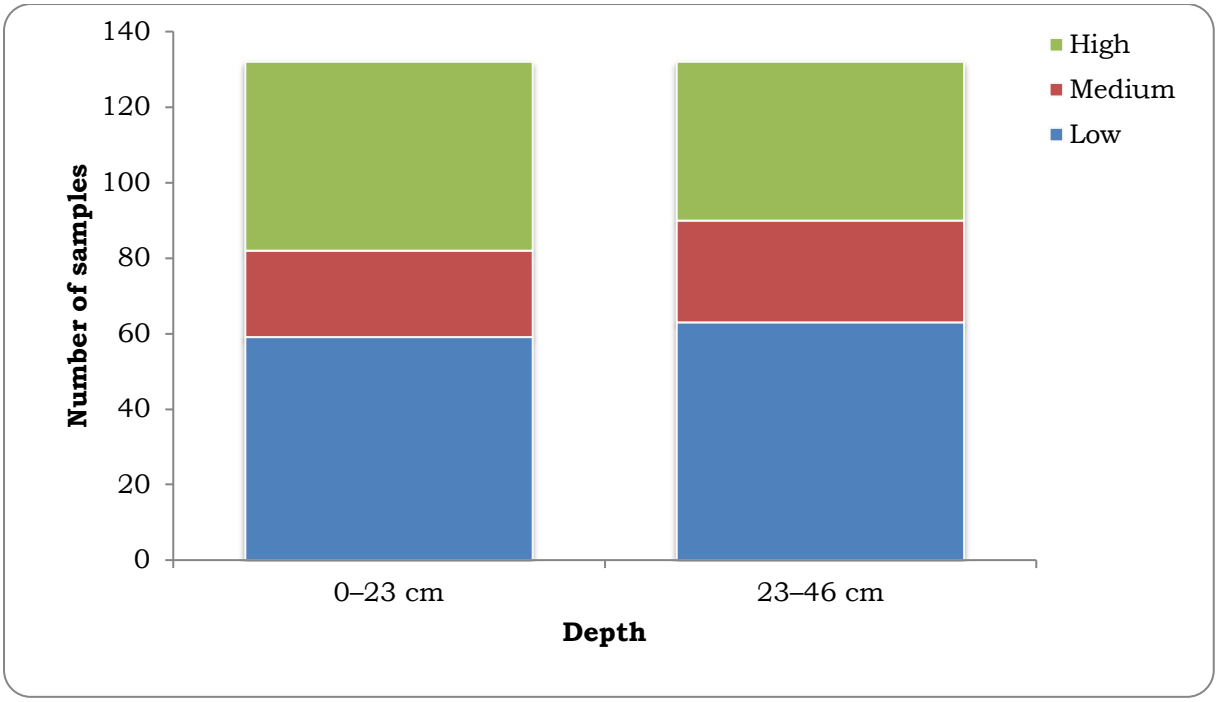



Fig. 2. Sulphur fertility classes by depth for tea-soil samples collected at 0-23 cm and 23-46 cm.

***Sub-surface sulphur distribution***

Sub-surface sulphur status also varied markedly among tea estates (Table 2). Bilashcherra Experimental Farm recorded the highest mean subsurface sulphur concentration (35.76 mg/kg), and comparatively high values were also observed at Kazi (24.21 mg/kg), Karotoa (19.89 mg/kg), and Neptune (19.42 mg/kg). In contrast, Allynugger (3.03 mg/kg), Malnicherra (3.94 mg/kg), and BTRI Farm (4.43 mg/kg) recorded the lowest mean values, while Jagcherra (7.20 mg/kg), Sathgao (6.97 mg/kg), and Rajghat (8.66 mg/kg) also remained in the low range.

Mean sulphur increased with depth in Bilashcherra Experimental Farm, Neptune, and Kazi and Kazi, but declined sharply in Karnafuli, indicating that vertical sulphur distribution in tea soils is estate-specific rather than uniform. Recent work in tea plantations has similarly shown that sulphur availability can vary across sites and environmental gradients rather than following a single, uniform pattern, suggesting that local soil and landscape controls are important in shaping the availability of sulphur (Wang *et al.*, 2025a).

Table 2. Estate-wise statistics of available sulphur in sub-surface soils (23-46 cm) of tea estates in Bangladesh.

| Tea Estate | No. of samples | Mean (mg/kg) | Minimum (mg/kg) | Maximum (mg/kg) | SD |
|---|---|---|---|---|---|
| Bilashcherra Experimental Farm | 21 | 35.76 | 22.00 | 61.00 | 9.08 |
| Kazi & Kazi | 14 | 24.21 | 9.00 | 35.00 | 8.25 |
| Karotoa | 9 | 19.89 | 15.00 | 26.00 | 3.79 |
| Neptune | 10 | 19.42 | 8.46 | 59.06 | 16.74 |
| Oodaleah | 9 | 13.20 | 1.89 | 30.94 | 10.76 |
| Karnafuli | 8 | 12.33 | 3.88 | 20.97 | 5.96 |
| Rajghat | 9 | 8.66 | 1.39 | 22.45 | 8.34 |
| Patrakhola | 5 | 8.06 | 2.57 | 15.32 | 4.90 |
| Jagcherra | 11 | 7.20 | 0.58 | 33.20 | 9.83 |
| Sathgao | 10 | 6.97 | 0.89 | 20.26 | 7.56 |
| BTRI Farm | 5 | 4.43 | 1.35 | 11.71 | 4.27 |
| Malnicherra | 10 | 3.94 | 0.95 | 6.92 | 1.93 |
| Allynugger | 11 | 3.03 | 0.59 | 9.25 | 2.54 |

***Relationship of available sulphur with Soil pH and organic matter***

Available sulphur showed significant positive relationships with both soil pH and organic matter at the two sampled depths (Table 3). In surface soil, available sulphur was positively related to soil pH ($r = 0.298$, $p < 0.001$; $n = 132$) and organic matter ($r = 0.406$, $p < 0.001$; $n = 132$). In sub-surface soil, the corresponding relationships were $r = 0.354$ ($p < 0.001$; $n = 132$) for soil pH and $r = 0.502$ ($p < 0.001$; $n = 132$) for organic matter. The stronger association with organic matter is agronomically plausible because it serves as a major reservoir of soil sulphur and contributes to sulphate release through mineralization (Scherer, 2009; Islam *et al.*, 2021).

The soil pH trend is illustrated in Figure 3. The relationship was positive at both depths, but the scatter indicates that soil pH influenced sulphur availability without fully determining it. Some estates already maintained adequate or high sulphur status, whereas others remained low at similar soil pH levels. This suggests that soil pH affected sulphur availability, alongside other site-specific controls such as organic matter supply, drainage conditions, and fertilizer history. Recent tea research has shown that soil pH significantly affects nutrient enrichment, plant growth, photosynthetic capacity, and leaf quality, while broader tea-soil analyses have also emphasized the central role of pH in nutrient balance and acidification processes (Jia *et al.*, 2024; Wang *et al.*, 2025b).

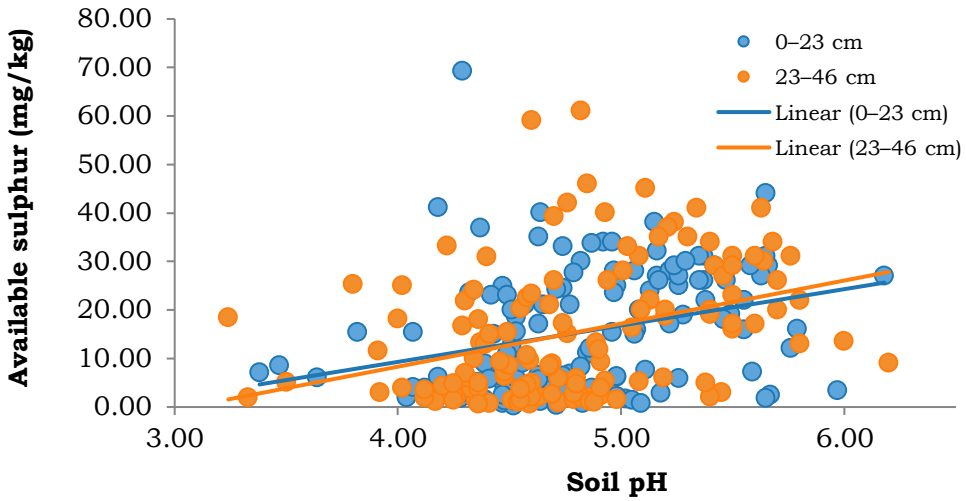



Fig. 3. Relationship between soil pH and available sulphur in tea soils at 0-23 cm and 23-46 cm depths.

The organic-matter trend is shown in Figure 4 and is more clearly positive, especially in the sub-surface layer. This pattern supports the central role of organic matter in storing and gradually releasing sulphur through mineralization. Maintenance of soil organic matter through litter return, management of pruning residues, and the use of organic amendments should therefore improve the resilience of sulphur supply over time (Scherer, 2009; Islam *et al.*, 2021). Recent research on tea fertilization has also shown that combined organic and chemical fertilization significantly increased soil organic matter and soil pH, thereby improving overall soil nutrient quality in tea plantations (Miao *et al.*, 2024; Narayan *et al.*, 2023).

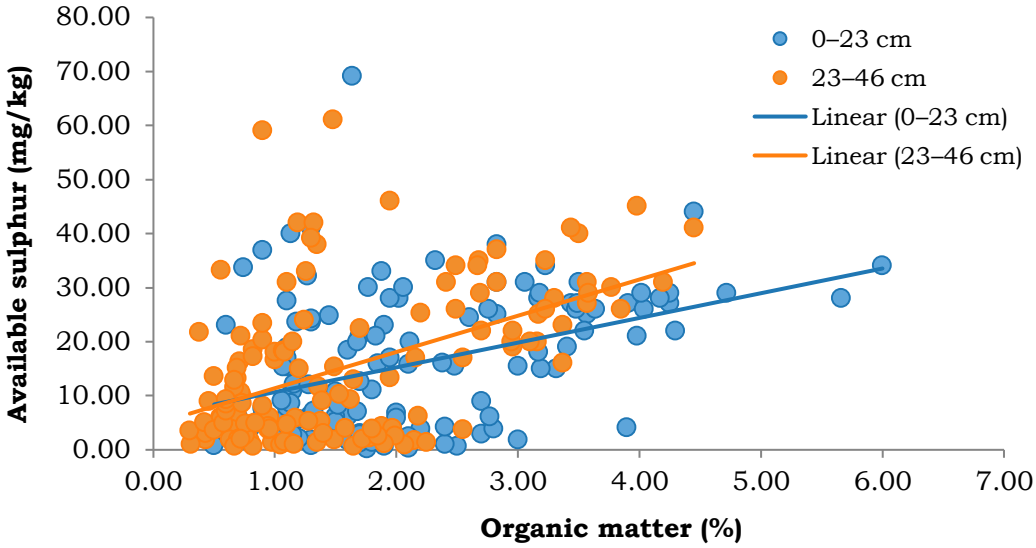



Fig. 4. Relationship between soil organic matter and available sulphur in tea soils at 0-23 cm and 23-46 cm depths.

Table 3. Pearson correlation coefficients of available sulphur with Soil pH and organic matter.

| Depth | Variable | n | Pearson r | p-value |
|---|---|---|---|---|
| 0-23 cm | Soil pH | 132 | 0.298 | <0.001 |
| 0-23 cm | Organic matter | 132 | 0.406 | <0.001 |
| 23-46 cm | Soil pH | 132 | 0.354 | <0.001 |
| 23-46 cm | Organic matter | 132 | 0.502 | <0.001 |

Overall, the results showed that sulphur deficiency remained common in tea-growing soils of Bangladesh, but the problem was not uniform. Some estates already maintained adequate or high sulphur status, whereas others fell well below the critical limit at both depths. Regular soil testing, balanced fertilization, and maintenance of soil organic matter should therefore be emphasized in nutrient management programs for tea. The dataset provides a useful baseline for site-specific sulphur fertilization and for improving nutrient stewardship in Bangladesh tea plantations. This interpretation is consistent with recent evidence showing that nutrient management in tea systems should account for local variation in soil condition, acidification, and organic matter status rather than relying on uniform recommendations (Wang *et al.*, 2025b; Miao *et al.*, 2024).

## Conclusion

The present study revealed considerable variation in available sulphur among tea estates in Bangladesh, although the overall mean sulphur concentration was very similar between the two sampling depths. Mean available sulphur was 15.61 mg/kg in the 0–23 cm layer and 15.47 mg/kg in the 23–46 cm layer, and the paired t-test indicated that the difference was not statistically significant. A large proportion of samples fell within the low to medium sulphur range, with 44.7% of surface soils and 47.7% of sub-surface soils classified as low in available sulphur, suggesting that sulphur deficiency remains an important concern in many tea soils of Bangladesh. Marked estate-wise variation was observed, with Bilashcherra Experimental Farm, Karnafuli, Kazi & Kazi, and Karotoa showing

relatively higher sulphur status, whereas Allynugger, Malnicherra, BTRI Farm, Jagcherra, and Sathgao had comparatively lower values. Available sulphur was positively and significantly related to both soil pH and organic matter at both depths, with the strongest relationship observed between sub-surface sulphur and organic matter. These findings indicate that sulphur availability in tea soils is influenced by both estate-specific conditions and general soil properties. Therefore, regular soil testing and estate-specific sulphur management should be emphasized to maintain balanced soil fertility and support sustainable tea production.

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# Effects of palm weevil larvae incorporation on proximate composition and mineral content of beef-type sausages

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**A B S T R A C T**

Palm weevil larvae (*Rhynchophorus phoenicis*), locally known as Akokono, are edible insects traditionally consumed in Ghana and represent a promising alternative protein resource for agricultural value addition and meat product innovation. This study evaluated the nutritional composition of beef-type sausages formulated with Akokono, focusing on proximate composition and mineral content. Akokono was incorporated into beef sausages at graded substitution levels ranging from 0% to 70%, and sausage samples were analysed using standard analytical procedures. The proximate composition of Akokono–beef sausages differed significantly among formulations ($p < 0.05$), with crude fibre ranging from 0.76–7.46%, ash 2.86–7.45%, protein 52.97–85.34%, and fat 5.56–31.77%. Mineral composition also varied significantly across treatments ($p < 0.05$). The sausage samples contained 0.84–1.19% phosphorus, 0.16–0.24% magnesium, 0.05–0.09% sodium, 0.33–0.44% calcium, 1.17–2.18% potassium, 10.68–26.64 mg/kg zinc, and 15.04–30.68 mg/kg iron. The results demonstrate that Akokono incorporation significantly affects the nutritional quality of beef-type sausages and highlight the potential of palm weevil larvae as a nutrient-rich, innovative agricultural protein resource for sustainable meat product development.

**Keywords:** Akokono, Protein content, Nutritional quality, Agricultural innovation, Insect-based meat products

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## Introduction

The increasing global demand for sustainable, nutritious, and affordable protein sources has intensified pressure on conventional livestock production systems. Rapid population growth, rising feed costs, environmental degradation, and concerns about greenhouse gas emissions and land use associated with meat production have stimulated interest in alternative protein sources that can complement or partially replace traditional animal proteins (FAO, 2013; van Huis *et al.*, 2015). Within this context, edible insects have emerged as promising components of sustainable agri-food systems due to their high feed conversion efficiency, relatively low environmental footprint, and favourable nutritional profiles (Rumpold and Schlüter, 2013; Halloran *et al.*, 2017).

Palm weevil larvae (*Rhynchophorus phoenicis*), locally known as Akokono, are traditionally consumed in several parts of West Africa, particularly in Ghana. Among the Asante communities, Akokono is valued for its palatability and perceived nutritional benefits. Scientific studies have confirmed that palm weevil larvae are rich in protein, lipids, and essential minerals, including iron, zinc, calcium, potassium, and phosphorus (Elemo *et al.*, 2011; Anankware *et al.*, 2015; Egonyu *et al.*, 2024). Despite this nutritional potential, the utilization of Akokono remains largely informal and limited to traditional preparation methods, with minimal integration into value-added or commercially processed food products. This limited utilization has constrained its wider

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acceptance, commercialization, and contribution to food and nutrition security (Anankware *et al.*, 2016; Sogari and Mora, 2019).

Processed meat products, such as sausages, provide a suitable matrix for incorporating alternative protein ingredients due to their comminuted structure, formulation flexibility, and widespread consumer acceptance. Previous studies have demonstrated that insect-based ingredients can be successfully incorporated into meat products, enhancing nutritional value while facilitating gradual consumer exposure to novel protein sources (Cruz-López *et al.*, 2022; Kolev *et al.*, 2024). However, the nutritional consequences of substituting beef with palm weevil larvae - particularly with respect to proximate compositions and mineral contents- remain insufficiently documented. A clear understanding of these effects is essential for guiding formulation optimization and supporting the development of nutritionally improved and sustainable meat products.

Therefore, this study evaluated the nutritional composition of beef-type sausages formulated with graded levels of palm weevil larvae. Specifically, the study assessed the proximate composition and mineral profile of Akokono–beef sausages, with the aim of providing scientific evidence to support the utilization of palm weevil larvae as a novel agricultural protein resource for sustainable meat product development

## Materials and Procedures

### *Study location*

The study was conducted at the Meat Science and Processing Unit of the Department of Animal Science and the laboratories of the Department of Food Science and Technology, all at the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana. Production of samples started, with trials beginning in September 2024, and final laboratory analyses were completed in November 2025.

### *Experimental materials*

Lean boneless beef was obtained fresh from the Kumasi Abattoir Company in Kumasi, Ghana. Ground culinary spices were purchased from Opoku Trading Supermarket, Kumasi. Natural hog casings with a diameter of 32 mm were used to stuff sausages. The equipment used for sausage preparation included a meat grinder fitted with a 15 mm sieve plate, a food processor, a manually operated sausage stuffer, a digital weighing balance, and a probe-type meat thermometer. Farmed Akokono larvae were obtained from the Legendary Food Research Centre.

### *Preparation of palm weevil larvae and lean beef*

Palm weevil larvae, obtained alive and active, were thoroughly washed under running potable water to remove adhering debris and surface contaminants. The larvae were subsequently sealed in sterile Ziplock bags to restrict movement and physiological activity, thereby minimizing post-harvest biochemical changes and preserving lipid and protein integrity. Both the palm weevil larvae (Akokono) and lean beef were then stored at −18 °C for 24 h prior to sausage production to stabilize the raw materials and ensure uniform processing conditions.

### *Formulations used in sausage production*

A negative control formulation containing only palm weevil larvae (Akokono) and additives was evaluated during preliminary trials; however, it exhibited poor binding capacity and weak textural characteristics. This observation aligns with previous reports indicating limited gelation and binding functionality of insect proteins when used alone in comminuted meat systems. Consequently, this formulation was excluded from the main experiment. A positive control consisted of minced beef mixed with ice, without Akokono inclusion. No additional water was added to the beef–Akokono formulations because of the larvae's inherently high moisture content. The prepared sausage batters were stuffed into 32 mm natural hog casings using a manually operated sausage stuffer and tied into uniform links to ensure consistency across treatments. Ground lean beef and palm weevil larvae (Akokono) were proportioned and allocated to the respective experimental treatments ($T_1$–$T_8$) according to the predefined formulation ratios presented in Table 1.

Table 1. Ingredients used in beef-type akokono sausage formulation.

| Ingredients (g) | Treatment | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ | $T_6$ | $T_7$ | $T_8$ |
| Akokono | 1400 | 1200 | 1000 | 800 | 600 | 400 | 200 | 0 |
| Beef | 600 | 800 | 1000 | 1200 | 1400 | 1600 | 1800 | 1600 |
| Salt | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| Ice | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 400 |
| Total | 2020 | 2020 | 2020 | 2020 | 2020 | 2020 | 2020 | 2020 |

*$T_1$–$T_7$ represent beef–type Akokono sausage formulations containing decreasing levels of Akokono (70%, 60%, 50%, 40%, 30%, 20% and 10%, respectively) with corresponding increases in beef proportion, while $T_8$ serves as the 100% beef control. All quantities are expressed in grams (g) on a formulation basis.*

### *Thermal processing and storage*

The sausages were scalded in a temperature-controlled water bath maintained at 80°C until an internal core temperature of approximately 72°C was achieved, as monitored using a calibrated probe-type meat thermometer. This thermal treatment was applied to ensure product safety and uniform heat penetration. Following scalding, the sausages were immediately cooled in cold water, surface-dried, appropriately labelled, and stored under frozen conditions (approximately −18°C) at the Department of Animal Science for subsequent physicochemical, nutritional and quality analyses.

### *Parameters evaluated*

*Proximate composition*

Proximate composition of farmed Akokono–beef sausage samples was determined using standard methods of the Association of Official Analytical Chemists (AOAC, 2023). Moisture content was determined by oven drying at 105°C to constant weight, ash content by dry ashing at 550°C, crude protein by the Kjeldahl method using a nitrogen-to-protein conversion factor of 6.25, and crude fat by Soxhlet extraction using petroleum ether. Carbohydrate content was calculated by difference. Proximate composition values were expressed on a dry matter (DM) basis, following moisture correction after oven drying.

### *Mineral analysis*

Mineral composition of the Akokono–beef sausage samples was determined using standard analytical procedures (AOAC, 2023). Dried and finely ground samples were dry-ashed and acid-digested to obtain clear solutions for analysis. Concentrations of calcium (Ca), magnesium (Mg), sodium (Na), potassium (K) and phosphorus (P) were determined and expressed as percentages (%), while iron (Fe) and zinc (Zn) were quantified and expressed as mg/kg. Calcium, magnesium, sodium, potassium, iron and zinc were analyzed using a true Atomic Absorption Spectrophotometer equipped with hollow cathode lamps and an atomization system, *iCE 3000 Series AAS* (Thermo Fisher Scientific, Waltham, MA, USA), whereas phosphorus was determined using a standard colorimetric method. Analytical accuracy and quality control were ensured using reagent blanks, calibration standards, and certified reference materials.

### *Experimental design and statistical analysis*

The experiment was laid out in a completely randomized design (CRD**)** comprising eight treatments ($T_1$–$T_8$**)** corresponding to graded levels of Akokono substitution, with three replications per treatment, each replicate consisting of 2 kg of sausage batter. Data generated from the physicochemical, nutritional, and quality analyses were subjected to one-way analysis of variance (ANOVA) using IBM SPSS Statistics (version 27). Differences among treatment means were determined using Duncan's Multiple Range Test, and statistical significance was declared at $p < 0.05$.

## Results and Discussion

### *Proximate composition*

As presented in Table 2, Akokono incorporation significantly influenced the proximate composition of beef-type sausages, particularly crude fibre, ash, protein, and fat contents ($p < 0.001$). Increasing levels of Akokono resulted in higher crude fibre (0.76–7.46%) and ash contents (2.86–7.45%), attributable to the chitin content and mineral richness of palm weevil larvae, respectively (Elemo *et al.*, 2011; van Huis *et al.*, 2015; Lisboa *et al.*, 2024). Conversely, crude

protein increased with higher beef inclusion, ranging from 52.97% in Akokono-rich formulations to 85.34% in the beef-only control, reflecting differences in protein density between insect biomass and beef (Choi *et al.*, 2017; Kim *et al.*, 2019). The proximate composition values reported in this study were expressed on a dry matter (DM) basis, thereby excluding moisture from the calculations. Consequently, the coexistence of relatively high crude protein and fat contents in Akokono-rich formulations is mathematically consistent. For example, in $T_1$, crude protein (52.97%), fat (31.77%), fibre (7.46%), and ash (3.88%) collectively account for 96.08% of the dry matter, leaving a small proportion attributable to nitrogen-free extract (carbohydrates by difference). This observation supports the compositional validity of the results and reflects the nutrient-dense nature of palm weevil larvae. Fat content declined markedly from 31.77% to 5.56% with decreasing Akokono levels, consistent with the relatively high lipid content of palm weevil larvae (Elemo *et al.*, 2011; Chamoun *et al.*, 2023). These results indicate that palm weevil larvae can be utilized as a novel agricultural protein resource to modify the nutritional profile of processed meat products.

Table 2. Proximate composition of beef-type kokono sausages

| Parameters | Treatment | | | | | | | | SEM | p-value |
|---|---|---|---|---|---|---|---|---|---|---|
| | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ | $T_6$ | $T_7$ | $T_8$ | | |
| Fiber | 7.46$^{g}$ | 2.53$^{c}$ | 5.06$^{e}$ | 6.35$^{f}$ | 4.50$^{d}$ | 1.83$^{b}$ | 0.76$^{a}$ | 0.87$^{a}$ | 0.49 | <0.001 |
| Ash | 3.88$^{b}$ | 4.85$^{c}$ | 7.03$^{g}$ | 5.06$^{d}$ | 2.86$^{a}$ | 5.62$^{e}$ | 7.45$^{g}$ | 6.55$^{f}$ | 0.30 | <0.001 |
| Protein | 52.97$^{a}$ | 54.05$^{b}$ | 59.95$^{c}$ | 68.50$^{d}$ | 69.40$^{e}$ | 72.61$^{f}$ | 81.55$^{g}$ | 85.34$^{h}$ | 2.32 | <0.001 |
| Fat | 31.77$^{h}$ | 25.66$^{g}$ | 23.19$^{f}$ | 19.09$^{e}$ | 17.51$^{d}$ | 15.76c | 6.72$^{b}$ | 5.56$^{a}$ | 1.75 | <0.001 |

*$^{abcdefgh}$Means in the same row with different superscripts are significantly different (p<0.001); $T_1$= 70% kokono + 30% beef; $T_2$= 60% kokono + 40% beef; $T_3$= 50% kokono + 50% beef; $T_4$= 40% kokono+ 60% beef; $T_5$ = 30% kokono + 70% beef; $T_6$ = 20% kokono + 80% beef; $T_7$ =10% kokono + 90% beef, $T_8$= 0% kokono + 100% beef; SEM= standard error of means.*

***Mineral composition of sausages***

Table 3 presents the mineral composition of beef-type Akokono sausages across the eight formulations ($T_1$–$T_8$). Significant differences ($p < 0.05$) were observed among treatments for all minerals analyzed, indicating that Akokono inclusion level substantially influenced mineral composition. Phosphorus, magnesium, sodium, calcium, potassium, zinc, and iron contents varied across formulations, reflecting differences in the proportion of Akokono relative to beef. In general, formulations containing higher proportions of Akokono exhibited elevated concentrations of both macro- and micro-minerals, consistent with the mineral-rich nature of palm weevil larvae.

The observed mineral profiles align with previous reports that identify palm weevil larvae as valuable sources of essential minerals, including iron, zinc, calcium, potassium, and phosphorus (Adobeze *et al.*, 2022; Rumpold and Schlüter, 2013).

Table 3. Mineral composition of sausages

| Parameter (%) | Treatment | | | | | | | | SEM | p-value |
|---|---|---|---|---|---|---|---|---|---|---|
| | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ | $T_6$ | $T_7$ | $T_8$ | | |
| P | 0.94$^{c}$ | 0.84$^{a}$ | 1.06$^{d}$ | 1.11$^{f}$ | 1.09$^{e}$ | 1.19$^{g}$ | 0.93$^{c}$ | 0.91$^{b}$ | 0.02 | <0.001 |
| Mg | 0.24$^{e}$ | 0.18$^{bc}$ | 0.19$^{d}$ | 0.18$^{bc}$ | 0.17$^{b}$ | 0.18$^{bc}$ | 0.16$^{a}$ | 0.16$^{a}$ | 0.26 | <0.001 |
| Na | 0.06$^{b}$ | 0.05$^{a}$ | 0.07$^{d}$ | 0.08$^{e}$ | 0.08$^{e}$ | 0.09$^{g}$ | 0.08$^{e}$ | 0.07$^{c}$ | 0.02 | <0.001 |
| Ca | 0.44$^{f}$ | 0.38$^{b}$ | 0.41$^{c}$ | 0.38$^{b}$ | 0.43$^{g}$ | 0.42$^{d}$ | 0.43$^{e}$ | 0.33$^{a}$ | 0.07 | <0.001 |
| K | 1.30$^{b}$ | 1.17$^{a}$ | 1.65$^{d}$ | 2.00$^{f}$ | 1.86$^{e}$ | 2.18$^{g}$ | 1.85$^{e}$ | 1.53$^{c}$ | 0.06 | <0.001 |
| Zn (mg/kg) | 13.16$^{ab}$ | 10.68$^{a}$ | 20.20$^{cd}$ | 20.55$^{cd}$ | 21.68$^{d}$ | 26.64$^{e}$ | 22.65$^{d}$ | 16.61$^{bc}$ | 1.08 | <0.001 |
| Fe(mg/kg) | 18.54$^{b}$ | 15.04$^{a}$ | 24.58$^{d}$ | 28.48$^{e}$ | 22.59$^{c}$ | 30.68$^{f}$ | 22.91$^{c}$ | 18.70$^{b}$ | 1.01 | <0.001 |

*$^{abcdefg}$Means in the same row with different superscripts are significantly different (p<0.001); $T_1$= 70% kokono + 30% beef; $T_2$= 60% kokono + 40% beef; $T_3$= 50% kokono + 50% beef; $T_4$= 40% kokono+ 60% beef; $T_5$ = 30% kokono + 70% beef; $T_6$ = 20% kokono + 80% beef; $T_7$ =10% kokono + 90% beef; $T_8$= 0% kokono + 100% beef; SEM= standard error of means.*

Phosphorus and magnesium levels were within ranges reported for processed meat and insect-enriched food systems (Espinales *et al.*, 2024), while sodium levels remained relatively low and within recommended limits for healthier meat products (WHO, 2012). Calcium and potassium contents were comparable to values reported for conventional and insect-based foods (Zhou *et al.*, 2022). Zinc and iron concentrations were within ranges typically reported for fresh and processed meats (Bohrer, 2017), suggesting that Akokono-enriched sausages can contribute meaningfully to dietary micronutrient intake (Lim *et al.*, 2013). Overall, Akokono incorporation enhanced the mineral profile of beef-type sausages, with moderate inclusion levels providing a balanced and nutritionally advantageous mineral composition suitable for product optimization

## Conclusions and Recommendations

The results of this study demonstrate that palm weevil larvae (*Rhynchophorus phoenicis*) can be successfully incorporated into beef-type sausages, significantly influencing their nutritional composition. Akokono inclusion increased fibre, ash, fat, and mineral contents, while beef-dominant formulations exhibited higher protein and moisture levels. The presence of chitin enhanced dietary fibre, and the incorporation of Akokono markedly improved the mineral profile of the sausages, particularly iron, zinc, potassium, calcium, magnesium, and phosphorus, without excessive sodium levels. Overall, sausages containing moderate levels of Akokono provided a balanced nutritional profile, combining improved micronutrient content with acceptable protein levels. It is therefore recommended that Akokono be incorporated at moderate substitution levels in beef-type sausages to maximize nutritional benefits**.** Further studies should explore shelf stability, mineral bioavailability, consumer perception at scale, and the optimization of processing techniques to support commercial adoption. These findings highlight palm weevil larvae as a nutritionally valuable and innovative agricultural protein resource with strong potential for value addition, product diversification, and sustainable meat product development.

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# Estimating avocado postharvest loss across its value chains and its determinants in Sidama and Gedeo areas, Southern Ethiopia

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**A B S T R A C T**

Fruit plays a vital role in enhancing nutrition security; however, it faces persistent postharvest losses due to socioeconomic, institutional, and biological factors. To reduce these losses, it is essential to identify the major causes and estimate the magnitude of loss to inform policy strategies. This study assessed the primary causes of avocado postharvest losses across the avocado value chain. A two-stage stratified sampling technique was employed to select sample respondents. Accordingly, a total of 212 producers were randomly selected from avocado-producing districts in the Sidama region and Gedeo zone. The results indicate that, on average, postharvest loss accounts for 19.02 percent of the total avocado harvest, despite avocados contributing 24.09 percent of the producers' total annual income. Across the value chain, collectors and retailers experienced losses exceeding 50 percent, whereas processors had losses below five percent. A multiple linear regression model was used to identify the determinants of postharvest avocado losses. The results show that harvesting with traditional sticks, unfavorable weather conditions, the use of soft storage materials, the presence of disease, and low frequency of extension contacts were significant factors contributing to postharvest losses. Therefore, the dissemination of improved harvesting and storage materials, combined with expanded extension support, is essential to minimizing postharvest losses in the area.

**Keywords:** Avocado, Gedeo, Multiple linear regression, Post-harvest Losses, Sidama

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## Introduction

Ethiopia has a comparative advantage in horticultural crop production due to its favorable climate, high domestic demand, and relatively low labor costs. Among these crops, fruits and vegetables are abundant sources of dietary fiber, vitamins, and minerals, and they also contribute significantly to economic growth and promote food and nutrition security (Banjaw, 2017). Across Ethiopia, a total of 116,284.63 hectares are dedicated to fruit cultivation. In this area, bananas account for approximately 59.95 percent of the cultivated area, followed by avocados at 17.98 percent (CSA, 2020). Most of these crops are produced by smallholder farmers and supplied to nearby markets. Although a wide variety of horticultural crops are cultivated, not all outputs reach consumers due to environmental, technical, and economic challenges that hinder harvesting, handling, and the effective distribution of produce from growers to consumers (Gebru and Belew, 2015).

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In addition, most fruits are highly susceptible to persistent postharvest losses, which exacerbate declines in output, limit food availability, and adversely affect the economy at both the household and national levels (Banjaw, 2017). Compared with other crops, the magnitude of fruit loss is particularly high due to their perishable nature, inadequate sorting to remove defects before storage, use of insufficient packaging materials, rough handling, poor cooling and temperature management, and contamination by pathogens (Kitinoja and Kader, 2002; Atanda *et al.*, 2011). As a result, an estimated 15-70% of horticultural crops incur postharvest losses (Misrak *et al.*, 2014). Practices that significantly contribute to these losses include improper harvesting and handling, inadequate storage facilities, insufficient transportation, poor packaging, and weak marketing systems (Banjaw, 2017).

However, postharvest management of most horticultural crops in Ethiopia has received inadequate attention, making it difficult to accurately account for losses during harvest and postharvest (Adugna *et al.*, 2011). Although the horticultural sector is growing, support for reducing postharvest loss and improving crop quality remains insufficient (Mohammed and Afework, 2016). To address this, since 2010, the Government of Ethiopia has been expanding mega and medium agro-industries to promote value addition through processing of agricultural outputs, aiming to boost foreign earnings and enhance economic growth under the Growth and Transformation Plan (GTP) (MoA, 2015). In southern Ethiopia, Sidama and Gedeo together account for approximately 29.6 percent of total avocado production (CSA, 2020). Among agro-industries, one mega and one medium industry were established in Sidama and Gedeo, respectively, and are currently processing avocado oil. The primary source of inputs for these industries is smallholder farmers' production. However, these industries face shortages in raw avocado supply in both quality and quantity due to production constraints, postharvest losses, and other socioeconomic and institutional factors.

Among the few studies on the determinants of avocado cultivation in Ethiopia, Benta *et al.* (2024) investigated the constraints of avocado production and marketing in southern Ethiopia using descriptive analysis. To the best of our knowledge, no studies have conducted a parametric analysis of the factors affecting avocado postharvest losses across its value chain in the area. Consequently, this study estimates avocado losses across the value chain and identifies their determinants using a robust multiple linear regression model. In doing so, the study contributes to identifying key intervention areas across the value chain to enhance sustainable productivity, value addition, and marketing of avocados.

## Research Methodology

### *Method of data collection and sampling techniques*

The study used primary data collected from avocado producers, traders, and processors during 2022. Before collecting household-level data, key informant interviews and focus group discussions were conducted to identify constraints in avocado production, including postharvest losses, and to understand the role of local institutions in its management. A two-stage sampling technique was then employed to select the sample respondents. In the first stage, districts with high avocado production potential were selected. In the second stage, two kebeles from each district were chosen based on their relative production potential. A total of 212 respondents were selected from both study areas, with 107 from the Sidama region and 105 from the Gedeo zone, using random sampling. The distribution of samples across the respective districts is presented in Table 1.

Table 1. Sample sizes from selected districts

| Region/Zone | Sample districts | Sample size | Frequency |
|---|---|---|---|
| Sidama Region | Aleta wondo | 35 | 16.51 |
| | Wondo Genet | 35 | 16.51 |
| | Dale | 37 | 17.45 |
| Gedeo Zone | Yirgachefe | 32 | 15.09 |
| | Dilla zuria | 39 | 18.40 |
| | Wonago | 34 | 16.04 |

### *Method of data analysis*

The collected data were analyzed using both non-parametric (descriptive) and parametric (econometric) methods. Descriptive statistics included the mean, percentage, frequency distribution, and standard deviation. A multiple linear regression model was employed to estimate population parameters and identify the causes of postharvest avocado loss.

The MLR model was employed to identify the causes of avocado postharvest loss (PHL) because the dependent variable, the amount of postharvest loss, is continuous and measured in kilograms. Twelve explanatory variables were considered as potential factors influencing PHL. The nature of these variables varies. Sex, storing materials, weather conditions, and disease are dummy variables, while harvest, education, age, family size, extension contact, distance to the nearest market, tropical livestock unit (TLU), and annual income of the respondents are continuous or discrete variables, depending on their characteristics. To overcome the estimation failure of ordinary least squares, robust estimation was employed.

$$Y_i = f(x_i, \beta) + \epsilon_i \text{ ---------- (1)}$$

Where,

$Y_i$ is the amount of avocado PHL in kilograms, and xi is a vector of independent variables. These are harvest, sex, storage materials, weather conditions, disease, education, age, family size, extension contact, distance to the nearest market, tropical livestock unit (TLU), and annual income of the respondents; $\epsilon_i$ is the error term.

## Results and Discussion

### *Socioeconomic characteristics of sample households*

The average postharvest loss (PHL) of avocados is 309.79 kilograms per year, with a range of 1 to 2,600 kilograms per year. The mean harvested amount of avocado fruit is 1,939.58 kilograms, with a range of 32 to 63,300 kilograms. This indicates that the area has high potential for avocado production, with postharvest loss representing a significant production constraint. Among the total sample, 83 percent of respondents were male, and 17 percent were female. The mean educational level of respondents is approximately seven grades. The average age and family size of respondents are 42.41 years and seven persons, respectively. Regarding storage practices, 34 percent of respondents used wooden hard-covered materials, while the remainder used jute sacks or baskets, indicating that only a minority of producers employ materials that protect avocados from damage.

Regarding production challenges, 87 percent of respondents reported that last year's weather conditions were unfavorable for avocado production, contributing to postharvest losses. Similarly, 45 percent of respondents reported that the disease affected avocado crops, resulting in additional postharvest losses. The average extension contact is 2.52 days per year, the average distance to the market is 3 kilometers, and the mean tropical livestock unit (TLU) is 1.44. The average annual income of respondents, derived from sources such as annual and perennial crop sales, livestock and livestock product sales, and other on-farm and off-farm activities, is 24,310 Birr.

Table 2. Socioeconomic and institutional variables of sample respondents.

| Variables | Mean | St.Dev | Min | Max |
|---|---|---|---|---|
| PHL in kilograms | 309.79 | 480.15 | 1 | 2600 |
| Harvested amount in kilograms | 1939.58 | 4850.07 | 32 | 63300 |
| Sex | 0.83 | 0.37 | 0 | 1 |
| Education in grades completed | 6.53 | 3.60 | 0 | 15 |
| Age | 42.41 | 14.54 | 14 | 85 |
| Family size | 6.58 | 2.53 | 0 | 12 |
| Storing materials | 0.34 | 0.48 | 0 | 1 |
| Weather condition | 0.87 | 0.34 | 0 | 1 |
| Disease | 0.45 | 0.49 | 0 | 1 |
| Extension contacts | 2.52 | 2.73 | 0 | 20 |
| Market distance | 3.003 | 3.12 | 0.1 | 15 |
| TLU | 1.44 | 1.48 | 0 | 6.88 |
| Income in 1000's Birr | 24.31 | 40.93 | 0 | 355.6 |

***Economic role of avocado fruit and its post-harvest losses***

According to the data, the average avocado production in the study area is estimated at 1,939 kilograms per year. By region, production in the Gedeo zone is higher than in the Sidama region, with averages of 2,042 and 1,839 kilograms, respectively. This difference may be attributed to the agricultural system in the Gedeo zone, which is predominantly agroforestry, with avocado as a major intercropped fruit. The harvested amount is further classified into sale, consumption, and postharvest loss. On average, postharvest loss accounts for approximately 19.03 percent of total avocado production. Despite this loss, avocados contribute significantly to farmers' annual income. The average annual income of avocado-producing farmers in the area is about 29.13 thousand Birr, with avocados contributing, on average, 24.09 percent of this income. This indicates that roughly one-fourth of farmers' income depends on avocados, highlighting the fruit's importance as both a source of income and a food. Across the study areas, the income share from avocados ranges from 22.66 to 25.51 percent.

Table 3. Avocado production, PHL, and income share of avocado production.

| Roles | Sidama Region | | Gedeo Zone | | Total | |
|---|---|---|---|---|---|---|
| | Mean | St.Err | Mean | St.Err | Mean | St.Err |
| Avocado produced in kilograms | 1839 | 295 | 2042 | 603 | 1939 | 333 |
| Avocado PHL share in percent | 19.03 | 1.52 | 19.01 | 1.17 | 19.02 | 0.96 |
| Annual income in 1000 Birr | 32.44 | 42.18 | 25.76 | 44.31 | 29.13 | 30.59 |
| Avocado income shares in percent | 25.51 | 2.31 | 22.66 | 2.52 | 24.09 | 1.71 |

All of the factors described above have either a positive or negative relationship with the amount of postharvest loss (PHL). Therefore, conducting a multiple linear regression model is necessary to quantify the relationship and determine the magnitude of their effects on avocado postharvest loss.

Table 4. Avocado amount collected and loss across its value chains.

| Roles | Retailers | | Collector | | Processors | |
|---|---|---|---|---|---|---|
| | Mean | St.Err | Mean | St.Err | Mean | St.Err |
| Avocado collected in kg | 5328.94 | 1837.79 | 9100 | 7100 | 2790 | 1710 |
| Avocado loss shares in percent | 55.39 | 11.89 | 60.5 | 20.5 | 4.8 | 3.8 |

Retailers: These are village-level buyers who purchase avocados primarily from producers. Due to the use of inappropriate harvesting materials at the farm level, the farm experiences significant avocado losses. The average loss at the retail stage is 55.39 percent, indicating that over half of the total amount purchased was lost.

Collectors: These are local assemblers who collect avocados from producers and retailers, then sell them to traders in other areas, such as Addis Ababa, Adama, and Jijiga, as shown in Figure 1. The average loss at the collector stage is 60.5 percent of the total collection.

Processors: These are small-scale processors who mainly produce juice. The average loss at this stage is about 4.8 percent, which is lower than the losses experienced by collectors and retailers. This relatively small loss occurs because processors purchase already ripe, high-quality fruit and process it daily. There is also a considerable amount of loss after collectors gather avocados from the locality. Before transporting them to the central market in Addis Ababa, collectors sort out damaged avocados, and these discarded fruits represent a loss for the collectors.



Fig. 1. Collector sorting damaged avocado at Aleta Wondo, Sidama.

***Multiple linear regression model results***

Twelve variables were used to identify the causes of postharvest avocado losses. Among them, five variables were found to significantly affect postharvest avocado losses. These are the amounts of avocados harvested, handling and storage materials, weather conditions, diseases, and the frequency of extension contacts. Among these variables, storage or handling materials and the frequency of extension contact have negative and significant effects, while the remaining variables have positive and significant effects. These results are consistent with prior expectations. Regarding model fitness, the $R^2$ is 78.39 percent, indicating that 78.39 percent of the variation in postharvest loss is explained by the explanatory variables included in the model.

Table 5. Multiple linear regression model result.

| Variables | Coefficients | Standard Error |
|---|---|---|
| Harvest | 17.41*** | 3.22 |
| Sex of the respondent | -10.01 | 31.38 |
| Educational status of the respondent | -0.52 | 2.85 |
| Age of the respondent | 0.059 | 0.63 |
| Family size of the respondent | 3.55 | 3.75 |
| Storing materials for avocado | -56.68*** | 16.39 |
| Weather conditions | 48.63** | 23.07 |
| Disease of the avocado | 73.59*** | 28.15 |
| Extension contact frequency | -6.19* | 3.26 |
| Market distance | 5.58 | 4.99 |
| Tropical livestock unit | 2.56 | 7.18 |
| Income of respondent per year | -0.0004 | 0.0003 |
| Constant | -26.63 | 42.98 |
| *$R^2$* | *78.39* | |
| *Observations* | *212* | |

Harvest: Farmers in the study area use locally available materials to harvest avocados. These materials often result in mechanical damage to the fruit. During harvesting, most farmers use sticks that damage both immature and mature avocados. Damaged avocados tend to decay quickly or are lost within a short period after harvest. This implies that postharvest avocado loss is expected to increase with the amount harvested; that is, the higher the harvest, the greater the loss. Among the total sample, none of the farmers used improved harvesting sticks or technologies to reduce postharvest loss. Therefore, the amount of avocado harvested using locally available materials was used to evaluate the relationship between production levels and postharvest loss. The results indicate that postharvest avocado losses are strongly associated with harvested volume. According to the results presented in the table, avocado harvest is positively associated with postharvest loss. Specifically, for each additional 100 kilograms harvested, postharvest loss increases by an average of

17.41 kilograms. This finding, which highlights the contribution of improper harvesting materials to postharvest fruit losses during harvesting, is consistent with prior studies (Obse *et al.*, 2021; Yebirzaf and Esubalew, 2021; Solomon, 2019; Seble, 2016; Humbe and Reneby, 2014; Victor, 2014).

Storing materials: In the study area, farmers use two types of storage materials after harvest. These are locally prepared wooden containers (such as kircho[1]) and jute sacks or baskets. The study evaluated which materials significantly reduce postharvest losses in avocado fruit. This evaluation was based on the premise that, compared with jute sacks or baskets used to store avocados after harvest, wooden containers have a hard shell that protects the fruit from mechanical damage during transportation and storage. Based on the results presented in the table, compared with jute sack users, farmers who use wooden materials experience, on average, 56.68 kilograms less postharvest avocado loss, holding other variables constant. This finding, which shows that hard-covered wooden and plastic materials help prevent postharvest loss of avocado, is consistent with prior studies (Obse *et al.*, 2021; Yebirzaf and Esubalew, 2021; Solomon, 2019; Seble, 2016; Victor, 2014; Humbe and Reneby, 2014).

Weather conditions: Weather can have both favorable and unfavorable effects on crop production, including fruit production. Unfavorable weather conditions that contribute to postharvest loss of avocado fruits include extreme temperature, relative humidity, air velocity, and atmospheric composition. Deviations in these conditions from normal levels can increase postharvest losses. According to the results, compared with respondents who reported favorable weather conditions for avocado production, those who reported unfavorable weather conditions experienced an average reduction of 48.63 kilograms of avocado due to postharvest loss. This finding is consistent with the studies conducted by Obse *et al.* (2021) and Victor (2014).

Disease: Disease is a major cause of postharvest avocado losses, leading to fruit decay and the discarding of damaged produce. Disease is a location-specific problem, and it was included to evaluate the magnitude of its effect on postharvest loss. Based on the results, sample respondents who reported that disease is a problem for avocado production experienced, on average, 73.53 kilograms more in postharvest loss than those who reported that it is not a problem. This finding is consistent with the results reported by Solomon (2019) and Victor (2014).

Extension contacts: The provision of extension support improves agricultural production by providing information on managing avocados during both preharvest and postharvest stages and by helping identify potential markets with higher demand for avocados. Thus, it is hypothesized to reduce postharvest losses. It is measured by the number of contacts with extension personnel per year regarding avocado production and marketing. According to the results, for each additional day of extension contacts, the postharvest loss of avocado decreases by an average of 6.19 kilograms, holding other factors constant.

## Conclusion and Recommendation

The results of the study reveal that postharvest loss is a major production constraint for avocado in the area. It accounts for about 19.02 percent of total harvest loss, despite avocado contributing 24.09 percent of the annual income of producer farmers. A robust multiple linear regression model was employed to identify the causes of postharvest loss. Accordingly, harvesting practices, storage materials, weather conditions, disease, and extension contact were identified as significant contributors to postharvest loss. Among these factors, disease and unfavorable weather conditions contribute to increased postharvest losses. In addition, due to the use of traditional harvesting materials, every one-hundred-kilogram increase in harvest results, on average, in a loss of 17.41 kilograms. On the other hand, increased extension contact and the use of hard-covered storage materials reduce postharvest loss.

Consequently, a greater emphasis on improving avocado production is highly needed. Due to the lack of improved harvesting tools or methods, increased harvest has led to higher losses. Therefore, the dissemination of improved harvesting materials, such as tools that collect fruits in small bags, is necessary. In addition,

[1]Kircho is a locally prepared wooden storage material made from bamboo.

introducing improved varieties with shorter tree heights and fruits that can be easily collected manually would have an advantage over the tall local varieties. Although the use of soft storage materials increases postharvest loss, the popularization of wooden storage materials and the introduction of plastic materials for improved storage and packing are important. Furthermore, to reduce disease-related losses, strengthening research and development of disease control mechanisms is essential to minimize avocado losses in the area. Finally, expanding the reach of extension services to ensure effective dissemination of information on avocado production and marketing is crucial.

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# Leveraging rice bran as an alternative feed ingredient: Effects on growth performance, carcass traits, and economic efficiency of Japanese quail (*Coturnix japonica*)

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**A B S T R A C T**

The study was conducted to evaluate the potential use of rice bran (RB) as a partial substitute for conventional feed in the diet of Japanese quails (*Coturnix japonica*). A total of 240 unsexed, 2-week-old quails were randomly assigned to one of four dietary treatments (0%, 10%, 20% and 30%) in a completely randomized design, with six replicates per treatment and ten birds per replicate. Growth performance parameters, including feed intake, body weight gain, average daily gain (ADG), and feed conversion ratio (FCR), were recorded weekly. At the end of the experiment, two birds per replicate, closest to the mean cage weight, were selected for carcass evaluation. Results showed rice bran inclusion did not significantly ($P > 0.05$) influence final body weight, body weight gain, ADG, total feed intake, ADFI, and FCR. Nonetheless, at the starter phase, BW ($P = 0.0193$), BWG ($P = 0.0146$), TFI and ADFI ($P = 0.0010$), and FCR ($P = 0.0075$) were significantly affected by dietary treatments. From the results, the RB_20 diet recorded the highest BW (143.33 g), BWG (90.83 g), and ADG (4.33 g/day), significantly outperforming the RB_30 group, which exhibited the lowest growth performance. Feed intake parameters showed a similar trend, with RB_20 significantly increasing ADFI (21.22 g/day) and TFI (445.50 g), while RB_0 recorded the lowest values. Conversely, FCR was adversely affected at higher inclusion levels, with RB_10 and RB_20 showing significantly higher FCR values than RB_0, whereas RB_30 exhibited intermediate efficiency. Carcass weight (95–102 g), thigh muscle yield (21.33–23.00 g), and wing weight (5.67–8.33 g) were also not significantly ($P > 0.05$) affected by dietary RB levels. Compared with the other treatment diets, the economic analysis showed that 30% RB inclusion resulted in the lowest feed cost (GH₵ 5.58). In summary, growth performance was optimized at 20% RB inclusion, suggesting improved nutrient utilization at moderate inclusion levels. Furthermore, increasing RB inclusion up to 30% in Japanese quail diets did not adversely affect growth performance or carcass traits, while significantly reducing feed costs. These findings highlight the potential of rice bran as a cost-effective alternative feed ingredient.

**Keywords:** Feed cost, Rice bran, Growth performance, Carcass traits, Japanese quail

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## Introduction

Poultry production is the largest contributor to the global meat supply, primarily due to its rapid growth, short maturity period, and efficient feed conversion (Zampiga *et al.*, 2021). Among poultry species, the Japanese quail (*Coturnix japonica*) has gained attention as a profitable alternative to chickens due to its rapid growth, early maturity, high egg production, and low production costs (Silva *et al.*, 2009; Lukanov

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*et al.*, 2018). Quails typically reach maturity within 6–7 weeks, produce up to 300 eggs annually, and thrive under intensive rearing systems, making them an attractive option for small, medium- and large-scale producers (Arunrao *et al.*, 2023; Roy's Farms, 2023).

Research indicates that feed costs remain a major constraint, accounting for approximately 70% of the total variable production cost in poultry systems (Oladokun and Johnson, 2012; Wongnaa and Awunyo-Vitor, 2023). This has encouraged the exploration of agro-industrial by-products such as rice bran and wheat bran as alternative feed ingredients. Previous research has shown that incorporating wheat bran into broiler diets does not compromise growth performance, regardless of the level of multi-enzyme supplementation (Idan, 2019; Idan *et al.*, 2023). Although rice bran is a nutrient-dense milling by-product, abundant in protein, fat, and antioxidants (Reema *et al.*, 2021; Tan *et al.*, 2023), two major challenges limit its application in poultry nutrition: high fiber content (which is poorly digested in monogastric animals) and rapid lipid oxidation. While several studies have evaluated rice bran in broilers, layers, and pigs (Ersin *et al.*, 2006; Tran *et al.*, 2016; Attia *et al.*, 2023), there is a paucity of information on its utilization and impacts in Japanese quails.

Therefore, the present study sought to evaluate the effects of increasing levels of rice bran on growth performance, carcass traits, and economic viability in Japanese quails.

## Materials and Methods

### *Experimental site*

The experiment was conducted at the Poultry Section of the Department of Animal Science, Kwame Nkrumah University of Science and Technology (KNUST), Ghana. The department lies at approximately 6.67°N latitude and 1.57°W longitude. The mean annual temperature is approximately 25.9°C, with annual rainfall averaging 1,100-1,500 mm. Relative humidity remains high throughout the year, averaging 84% in the morning and about 60% in the afternoon. These climatic conditions create a favorable environment for livestock and poultry research activities within the university.

### *Dietary treatment and experimental design*

Dietary treatments were assigned using a Completely Randomized Design (CRD). Four treatments were defined by replacing portions of the basal diet with rice bran at 0%, 10%, 20%, and 30%, with each treatment replicated six times. The details of the treatments are as follows; RB_0 = Control diet with no rice bran, RB_10 = Diet formulated with 10% rice bran, RB_20 = Diet formulated with 20% rice bran and RB_30 = Diet formulated with 30% rice bran

### *Feed formulation*

For both the starter and grow-finisher phases, the basal diet was modified by increasing the rice bran (RB) level, resulting in four experimental diets. All diets were formulated to be isocaloric and isonitrogenous. All the feeds were formulated at the Feed Manufacturing Centre in the Department of Animal Science, KNUST. Before mixing, the corn was ground using a hammermill (Kingdom Engineering Co. Ltd, Accra, Ghana). All dry ingredients, together with liquid fat (palm oil), were then blended in a 2-ton vertical mixer for 20 minutes. During the mixing process, samples of the complete feed were taken and kept in a freezer for subsequent chemical analysis. After mixing, the complete feeds were packaged, well labelled by treatment, and transported to the experimental site.

Table 1. Ingredient composition of starter, grower-to-finisher diets.

| Ingredient (kg) | Treatment Diets | | | |
|---|---|---|---|---|
| Starter Diet | RB_0 | RB_10 | RB_20 | RB_30 |
| Maize | 61.65 | 53.75 | 43.75 | 32.45 |
| Soybean Meal | 20.00 | 25.00 | 25.00 | 25.00 |
| Fish Meal | 8.00 | 5.00 | 5.00 | 5.00 |
| Wheat Bran | 6.00 | 0.00 | 0.00 | 0.00 |
| Rice Bran | 0.00 | 10.00 | 20.00 | 30.00 |
| Soybean Oil | 0.50 | 1.50 | 1.50 | 3.00 |
| Dicalcium Phosphate | 1.20 | 1.50 | 1.50 | 1.30 |
| Oyster Shell | 0.80 | 1.20 | 1.20 | 1.20 |
| L-Lysine | 1.00 | 1.00 | 1.00 | 1.00 |

| | | | | |
|---|---|---|---|---|
| DL-Methionine | 0.50 | 0.50 | 0.50 | 0.50 |
| Vitamin-Mineral Premix | 0.25 | 0.25 | 0.25 | 0.25 |
| Salt | 0.10 | 0.30 | 0.30 | 0.30 |
| Calculated Nutrient Composition | | | | |
| Crude Protein | 23.80 | 23.83 | 23.92 | 23.89 |
| Crude Fiber | 3.15 | 3.68 | 4.05 | 4.29 |
| ME (Kcal/kg) | 2949.7 | 2948.6 | 2941.9 | 2940.6 |
| Grower – Finisher Diet | | | | |
| Maize | 57.80 | 53.55 | 44.75 | 35.70 |
| SBM | 24.05 | 24.30 | 22.50 | 21.45 |
| Fish Meal | 8.00 | 8.00 | 8.00 | 8.00 |
| Wheat Bran | 7.00 | 1.00 | 1.00 | 0.00 |
| Rice Bran | 0.00 | 10.00 | 20.00 | 30.00 |
| Soy Oil | 0.10 | 0.30 | 0.90 | 2.00 |
| Dicalcium Phosphate | 1.20 | 1.20 | 1.20 | 1.20 |
| Oyster Shell | 0.50 | 0.50 | 0.50 | 0.50 |
| L-Lysine | 0.50 | 0.50 | 0.50 | 0.50 |
| DL-Methionine | 0.50 | 0.30 | 0.30 | 0.30 |
| Vitamin-Mineral Premix | 0.25 | 0.25 | 0.25 | 0.25 |
| Salt | 0.10 | 0.10 | 0.10 | 0.10 |
| Calculated Nutrient Composition | | | | |
| Crude Protein % | 21.076 | 21.181 | 21.027 | 21.026 |
| Crude Fiber | 3.398 | 3.778 | 4.525 | 5.212 |
| ME, Kcal/kg | 3,053.2 | 3,045.7 | 3,040.6 | 3,039.9 |

### *Birds and bird husbandry*

The feeding trial, spanning from 14 to 54 days of age, was conducted in two phases: starter (days 14 – 35) and grower-finisher (days 29 – 54). A total of two hundred and forty (240) two-week-old straight-run Japanese quails were procured from a local hatchery in Ejisu-Besease in the Ashanti Region of Ghana for the study. Birds with similar body weights were randomly allocated to 24 cages with 10 birds per cage. Fresh wood shavings were used as litter, and each cage was equipped with a plastic feeder and drinker. Paper boxes were placed beneath the cages to collect droppings and prevent contamination between units. Feed and water were provided *ad libitum* throughout the study.

### *Data collection*

*Growth performance measurement*

Body weight (BW) and feed consumption were recorded for each cage every week by weighing the birds and the remaining feed in the feeders. The BW of the quails and feed disappearance were used to calculate total feed intake, final body weight, body weight gain, average daily gain (ADG), and average daily feed intake (ADFI). Mortality was recorded daily, and the BW of any dead birds was included in the total cage weight and used to adjust feed intake data, thereby ensuring accurate calculation of the feed conversion ratio (FCR).

*Carcass characteristics measurement*

At the end of the trial, two birds per replicate with body weights close to the cage average were selected and humanely slaughtered for carcass evaluation. Parameters measured included defeathered weight, thigh muscle yield, edible organ weights, and intestinal weight and length.

*Economic analysis*

For economic viability, feed costs were estimated using market ingredient prices (as of May 8, 2024) and their corresponding dietary proportions. The total feed cost was calculated by multiplying the ingredient cost by the total feed intake per treatment, and the feed cost per kilogram of gain was determined as described by Frempong *et al.* (2019).

### *Statistical analysis*

The experimental data were analyzed using one-way analysis of variance (ANOVA) with the GLIMMIX procedure of SAS 9.4M8 (SAS Institute, 2023). The statistical model accounted for the effects of rice bran inclusion levels on growth performance and carcass characteristics of Japanese quails. When significant differences were detected ($P < 0.05$), means were separated using

Tukey's pairwise comparison test. The statistical model used was:

$Y_{ijk} = \mu + \alpha_i + e_{ijk}$
where:
$Y_{ijk}$ = observed value of the dependent variable,
$\mu$ = overall mean,
$\alpha_i$ = fixed effect of inclusion levels of rice bran (i = 1, 2, 3)
$e_{ijk}$ = random error term assumed to be normally distributed with mean zero and constant variance.

## Results

### *Growth performance*

The effects of rice bran inclusion on the growth performance of starter and grower-finisher Japanese quails are shown in Tables 2 and 3. Based on the results, the initial body weight (IBW) of quail chicks did not differ significantly (P > 0.05) among dietary treatment groups. In the starter phase, rice bran inclusion significantly influenced growth performance. Total feed intake (TFI), body weight (BW), average daily feed intake (ADFI), average daily gain (ADG), and feed conversion ratio (FCR) were all influenced by rice bran inclusion. Quails fed RB_20 had the highest final BW (143.33 g), which was significantly (P < 0.05) greater than that of quails fed RB_30 (131.67 g). The BWs of the RB_0 (135.83 g) and RB_10 (137.50 g) groups were intermediate and not statistically different from those of the RB_20 or RB_30 groups. A similar pattern was observed for BWG, ADG, TFI, and ADFI. The RB_20 group recorded the highest BWG (90.83 g) and ADG (4.33 g/bird/day), which were significantly higher (P < 0.05) than the RB_30 group (79.17 g and 3.77 g/bird/day, respectively). ADFI of the RB_20 group was the highest (21.22 g/bird/day), similar to that of the RB_10 group (20.20 g/bird/day), and significantly higher (P < 0.05) than those of the RB_0 (17.07 g/bird/day) and RB_30 (17.82 g/bird/day) groups. The control group had the lowest ADFI. A similar pattern was observed for total feed intake (TFI), with the RB_20 group consuming the most feed (445.50 g) during the starter period. For the FCR, the most efficient was observed in the control group (2.64), which was significantly better (P < 0.05) than the RB_10 (3.09) and RB_20 (3.11) groups. The FCR of the RB_30 group (2.85) was intermediate and not significantly different from the control or the higher-inclusion groups (RB_10 and RB_20).

Table 2. Effects of rice bran on growth performance of starter Japanese quail.

| Growth Parameters (g) | Treatment Diets | | | | | |
|---|---|---|---|---|---|---|
| | RB_0 | RB_10 | RB_20 | RB_30 | SEM | P-Value |
| IBW | 54.17 | 52.50 | 52.50 | 52.50 | 2.1731 | 0.8292 |
| BW | 135.83$^{ab}$ | 137.50$^{ab}$ | 143.33$^{a}$ | 131.67$^{b}$ | 3.3541 | 0.0193 |
| BWG | 84.17$^{ab}$ | 85.00$^{ab}$ | 90.83$^{a}$ | 79.17$^{b}$ | 3.1950 | 0.0146 |
| ADG | 4.01$^{ab}$ | 4.05$^{ab}$ | 4.33$^{a}$ | 3.77$^{b}$ | 0.1081 | 0.0146 |
| ADFI | 17.07$^{c}$ | 20.20$^{ab}$ | 21.22$^{a}$ | 17.82$^{bc}$ | 0.6855 | 0.0010 |
| TFI | 358.33$^{c}$ | 424.17$^{ab}$ | 445.50$^{a}$ | 374.17$^{bc}$ | 20.3644 | 0.0010 |
| FCR | 2.64$^{b}$ | 3.09$^{a}$ | 3.11$^{a}$ | 2.85$^{ab}$ | 0.1365 | 0.0075 |

$^{abc}$*Means within a row with different superscripts are significantly different at (P < 0.05). RB_0 = Control dirt (no RB); RB_10 (10% RB inclusion); RB_20 (20% RB inclusion); RB_30 (30% RB inclusion); IBW = Initial Body Weight; BW = Body Weight at the end of starter phase; BWG = Body Weight Gain; TFI = Total Feed Intake; ADFI = Average Daily Feed Intake; ADG = Average Daily Gain; SEM = Standard error of the means.*

For the grower-to-finisher phase, no significant (P < 0.05) differences were observed among treatments for any growth performance parameters, indicating that the earlier effects did not persist.

### *Carcass traits*

The results on carcass characteristics, evaluated at the end of the study, are presented in Table 4. Results showed no significant differences (P > 0.05) among the dietary treatments for any of the carcass parameters measured. This indicates that incremental inclusion of rice bran up to 30% of the diet had no measurable effect on the yield of valuable carcass components, such as breast, thighs, and wings, or on the overall dressing percentage. The uniformity in carcass traits across all groups suggests that the energy and nutrient intake were sufficient to support standard muscle and skeletal development, irrespective of the fiber level introduced by rice bran.

Table 3. Effects of rice bran on the growth performance of grower-to-finisher Japanese quail.

| Growth Parameters (g) | Treatment Diets | | | | | |
|---|---|---|---|---|---|---|
| | RB_0 | RB_10 | RB_20 | RB_30 | SEM | P-Value |
| FBW | 168.00 | 170.92 | 165.33 | 153.92 | 7.4546 | 0.1475 |
| BWG | 116.33 | 118.42 | 112.83 | 101.42 | 8.5490 | 0.2272 |
| ADG | 4.16 | 4.23 | 4.03 | 3.62 | 0.3048 | 0.2201 |
| ADFI | 24.73 | 28.51 | 28.63 | 27.17 | 1.9249 | 0.1849 |
| TFI | 692.50 | 798.33 | 801.67 | 760.83 | 53.9019 | 0.1851 |
| FCR | 4.13 | 4.66 | 4.85 | 4.98 | 0.3181 | 0.0675 |

*[abc]Means within a column with different superscripts are significantly different at (P < 0.05). RB_0 = control group; RB_10 = 10% rice bran inclusion; RB_20 = 20% rice bran inclusion; RB_30 = 30% rice bran inclusion. IBW = Initial Body Weight; FBW = Final Body Weight; BWG = Body Weight Gain; TFI = Total Feed Intake; ADFI = Average Daily Feed Intake; ADG = Average Daily Gain; SEM = Standard error of the mean.*

Table 4. The Effects of increasing levels of rice bran on the carcass traits of quails.

| Carcass traits (g) | Treatment Diets | | | | | |
|---|---|---|---|---|---|---|
| | RB_0 | RB_10 | RB_20 | RB_30 | SEM | P-Value |
| Leg | 4.67 | 4.33 | 2.33 | 3.67 | 1.2472 | 0.3201 |
| Lung | 1.13 | 1.34 | 1.09 | 0.99 | 0.1604 | 0.2433 |
| Neck | 8.67 | 6.67 | 4.33 | 7.67 | 2.4267 | 0.3799 |
| L. intestine | 2.67 | 2.33 | 2.33 | 2.67 | 0.4714 | 0.8018 |
| Spleen | 0.37 | 0.16 | 0.05 | 0.07 | 0.2131 | 0.4588 |
| Thigh | 22.33 | 21.33 | 23.00 | 21.33 | 1.9149 | 0.7812 |
| Wings | 7.67 | 5.67 | 8.33 | 6.67 | 2.66 | 0.7663 |
| Shank | 2.37 | 2.33 | 2.60 | 2.57 | 0.2273 | 0.5692 |
| S. intestine | 6.67 | 4.33 | 7.33 | 5.33 | 1.0274 | 0.0729 |
| Proventriculus | 0.54 | 0.37 | 0.61 | 0.60 | 0.1281 | 0.3112 |
| Carcass weight | 95.00 | 102.00 | 100.00 | 95.00 | 7.9451 | 0.7231 |

*[abc]Means within a column with different superscripts are significantly different at (P < 0.05). RB_0 = control group; RB_10 = 10% rice bran inclusion; RB_20 = 20% rice bran inclusion; RB_30 = 30% rice bran inclusion. SEM = Standard error of the means.*

***Economic viability***

The impact of dietary rice bran inclusion on production economics is presented in Table 5. A reduction in the feed cost per kg was observed with progressive RB inclusion, declining from ₵6.26 in the RB_0 diet to ₵5.58 in the RB_30 diet. However, the key metric of economic efficiency, the feed cost per unit of weight gain, was most favorable for the control diet (RB_0) at GH₵21.19/kg. This result indicates that the compromised feed conversion ratios and growth rates associated with higher rice bran levels negated the initial savings in feed ingredient costs, rendering the control formulation the most economically viable strategy under the present experimental conditions.

Table 5. Economic viability analysis of using rice bran as an ingredient in starter-to-finisher quail diet (0-7 weeks).

| Parameters | Treatment Diets | | | |
|---|---|---|---|---|
| | RB_0 | RB_10 | RB_20 | RB_30 |
| Total feed intake (g) | 1049.82 | 1222.17 | 1247.17 | 1135.00 |
| Feed cost (₵) per kg | 6.26 | 6.14 | 5.83 | 5.58 |
| Cost of feed per gain (₵/kg) | 21.19 | 23.80 | 23.20 | 21.85 |

*Total feed intake = the addition of total feed intake for each treatment from the starter to the finisher phase. Feed cost = (total feed cost for two phase/2)/100 kg; Cost of feed per gain = (FCR for each treatment at starter and grower to finisher phase/2) *feed cost per kg*

## Discussion

The present study demonstrated a phase-dependent response of Japanese quail to dietary rice bran, revealing a trade-off between growth stimulation and feed efficiency. During the starter phase, birds fed 20% rice bran had higher body weight and weight gain, primarily due to increased feed intake, indicating good palatability and a favorable nutrient profile (Aljuobori *et al.*, 2017). Similar early growth responses have been reported by Attia *et al.* (2023). However, this advantage was accompanied by poorer feed conversion ratios in the RB_10 and RB_20 groups, reflecting reduced nutrient utilization due to the high fiber content and antinutritional factors, such as phytic acid, in rice bran (Saeed *et al.*, 2019). At 30% inclusion, both feed intake and growth declined, suggesting that excessive fiber reduced dietary digestibility and voluntary feed intake.

The lack of significant differences during the grower–finisher phase indicates that quails adapted to the dietary fiber as their digestive capacity and cecal microbial activity increased with age (Sharma *et al.*, 2020). This adaptation eliminated both the early growth advantage observed at 20% inclusion and the depression seen at higher levels, resulting in comparable final performance across treatments. Similar findings have been reported in broilers and quails by Varzaru *et al.* (2020) and Yakubu *et al.* (2024). Other studies (Wu *et al.*, 2019; Sun *et al.*, 2016) have reported inconsistent outcomes, with variations attributed to differences in rice bran species, processing methods, energy content, and phytate levels.

Carcass characteristics were not affected by dietary treatments, consistent with similar final body weights and with previous reports (Attia *et al.*, 2023; Varzaru *et al.*, 2020). This indicates that rice bran can be included in quail diets without adversely affecting carcass yield at market age.

Although rice bran reduced the feed cost per kilogram, the control diet remained economically superior due to its better feed conversion efficiency. This confirms that lower feed costs do not necessarily translate into lower production costs. Nevertheless, studies such as Nguyen *et al.* (2022) show that enzyme supplementation can alleviate the anti-nutritive effects of fiber and improve the economic value of rice bran-based diets. Therefore, the full nutritional and economic potential of rice bran for quail feeding may be realized through appropriate processing or the inclusion of enzymes.

In conclusion, the inclusion of rice bran in quail diets yielded positive outcomes. The 20% level improved feed intake and early growth, while birds later adapted and maintained growth comparable to the control. This underscores the potential of rice bran as a practical and nutritious alternative feed resource for quails. Further research on enzyme supplementation, particularly phytase and xylanase, may improve nutrient availability and maximize the feeding value of rice bran in poultry diets.

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# Production and thermophysico-chemical characterization of charcoal briquettes from anaerobic fermentation digestate

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**A B S T R A C T**

Wood energy valorization dominates and accelerates deforestation with negative consequences for climate change. To reduce pressure on forests and mitigate climate change, this study proposes a sustainable solution aimed at producing ecological charcoal briquettes from digestates derived from cow dung and *Titonia diversifolia*. For this purpose, digestates from a 45-day mesophilic anaerobic co-digestion were dried to 8% moisture content over 35 days. The dried digestates were then submitted to uncontrolled pyrolysis. The parallelepiped and the cylindrical charcoal briquette were produced and tested. The results are as follows: the maximum pyrolysis temperature reached 390°C. The produced biochar was compressed into parallelepiped and cylindrical briquettes. Physicochemically, no difference between the two shapes was observed. Thermally, the heating value of the cylindrical and parallelepiped briquettes was 19 kJ/kg. Practically, the cylindrical shape, although less energy-efficient per unit of time, offers better heat utilization efficiency (a greater amount of water evaporated for an equivalent mass consumed), while the parallelepiped shape is characterized by higher instantaneous power, but with greater heat losses to the environment. Finally, optimizing the geometry and pressing of briquettes is essential to improving the efficiency and sustainability of biofuels, particularly in low-resource artisanal contexts.

**Keywords:** Climate change, Pyrolysis, Anaerobic codigestion, Charcoal briquettes, Shape, Digestate

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## Introduction

Energy demand in developing countries is growing rapidly due to population growth and economic expansion, with a nation's energy consumption profile reflecting its socio-economic level (Tanyi *et al.*, 2023; Gebrezgabher *et al.*, 2025). To meet these growing needs, fossil fuels such as oil, coal, and natural gas remain widely used (Ngosong *et al.*, 2024). However, these resources are limited, and their exploitation has significant environmental impacts. Actually, the world is facing high $CO_2$ emissions, contributing to an estimated increase in global temperature of 2.4-2.8°C by 2100 (Friedlingstein *et al.*, 2023). The intensive use of coal, kerosene, and petroleum in heat production and transportation industries contributes significantly to these emissions, while high production costs often make these resources inaccessible to developing countries (Shittu, 2024). In many developing countries, limited access to expensive alternative energy sources leads people to focus on biomass, a local, abundant, and renewable resource available close to rural areas (Babayomi,

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2022; Nguyen *et al.*, 2024). In Cameroon, approximately 226.9 million tons of agricultural residues and 22.5 million hectares of forest are available each year (Tanyi *et al.*, 2023; Fokeng, 2020), making biomass the primary source of energy for cooking and heating (Kouer, 2023). However, the lack of control over cutting schedules and the physical and chemical composition of biomass limit its energy efficiency and lead to negative environmental and health impacts, such as deforestation and exposure to smoke and fine particles, which are responsible for respiratory diseases and lung infections (Elbayoumi, 2023; Chowdhury, 2025; Sheikh Ali, 2024).

Furthermore, in the context of a circular economy, the recovery of by-products from processes such as anaerobic codigestion of digestates helps reduce environmental pollution and optimize resource use for more significant economic purposes. Indeed, digestates from anaerobic codigestion are widely used in agricultural production as organic fertilizers, and extensive research has established conclusive evidence of their contribution to agricultural yields. Although anaerobic digestion (AD) digestates are used in agriculture, they are also a source of biomass for producing coal briquettes. Charcoal briquette production is a promising, relatively recent technology used in rural areas of developing countries, particularly in Cameroon (Sharma *et al.*, 2015).

Recovering this AD digestate through pyrolysis could be a sustainable and effective solution. This thermochemical process, carried out in the absence or with very low oxygen levels at temperatures between 300 and 700°C, enables the production of biochar, bio-oil, and synthesis gas (syngas) (Sheikh Ali, 2024). The proportions of these products depend on several parameters, such as temperature, residence time, and heating rate: rapid pyrolysis at high temperatures promotes the production of bio-oil, whereas slow pyrolysis at moderate temperatures favors the formation of biochar (Irfan *et al.*, 2016). Charcoal briquettes are very useful for economic purposes (meat and fish charcoal traders, agroindustries combustion) and social purposes (households). Briquettes are safer for the environment than the raw materials used in the combustion process (Nzali *et al.*, 2023; Zhao *et al.*, 2018). The optimal shape of charcoal briquettes remains a topic of discussion among researchers. Numerous studies have explored the manufacture of briquettes from various types of biomass: alfa (Debdoubi *et al.*, 2005) sesame stalk and coconut shells, rice straw (Gebrezgabher *et al.*, 2025; Panwar *et al.*, 2011), corn meal and rice husks and Jatropha seed cakes (Oladeji, 2010; Nsah-ko Tchoumboué *et al.*, 2020) mango leaves, eucalyptus leaves, sawdust and banana leaves (De Oliveira Maia *et al.*, 2014), as well as certain forest species such as *Arundinaria alpina* and *Prosopis juliflora* (Feleke *et al.*, 2020). Other studies have shown the effectiveness of sawdust (Kouakou and Emeruwa, 2020) or mixtures based on coffee husks and bagasse (Lubwama and Yiga, 2018). The results obtained by each of these studies remain satisfactory and applicable. Very little research has focused on the use of digestates from anaerobic digestion on the one hand, and on comparing briquette shapes based on their density, stability, combustion efficiency, and the energy consumption associated with their production. Yet this variable could be decisive in optimizing the energy and economic performance of briquetting. Ultimately, optimizing the geometry and pressing of briquettes is essential to improving the efficiency and sustainability of biofuels, particularly in low-resource artisanal contexts.

The main objective of this work is to produce and characterize charcoal briquettes physically, chemically, and thermally from AcoD digestates.

## Materials and Methods

### *Digestate obtention and processing*

Digestates were obtained from an anaerobic co-digestion reactor treating cow manure and Tithonia diversifolia in a 50:50 ratio (dry matter), with an HRT of 45 days. The raw digestate, with a moisture content of 90%, was dried in a dryer at 30°C for 35 days. The final moisture content of the digestate was 8%, which was less than 15%, ensuring an efficient thermochemical process (Faaij, 2013; Mata-Alvarez *et al.*, 2014). A total mass of dried digestate was 5.2 kg.

### *Briquette production*

*Biochar production*

Biochar was produced based on methods developed by Bridgwater (2012). In fact, 5.2

kg of dried digestate was pyrolyzed in a homemade double-chamber pyrolyser with a capacity of 72 liters (Figure 1). Low-rate pyrolysis was carried out. The woody stems of *Tithonia diversifolia* were used as fuel for pyrolysis. The temperature change inside the pyrolyser was monitored using an HT-9815 digital thermocouple (range: 0–1000°C; accuracy: ± 1°C). The total duration of the process was recorded using a stopwatch from ignition to the end of carbonization. At the end of pyrolysis, the biochar was left to cool, then collected and ground to a powder with a particle size of 0.001 millimeters.

The pyrolysis key parameters were as follows:

Heating rate (HR) was determined using equation 3

$$HR = \frac{\text{Average pyrolysis temperature}}{\text{Pyrolysis duration}} \quad (3)$$

Average pyrolysis temperature in °C; Pyrolysis duration in hours (h); Heating rate in °C/h

Biochar yield was determined using equation 4

$$\text{Biochar yield} = \frac{\text{biochar mass}}{\text{digestate mass}} \text{x } 100 \quad (4)$$

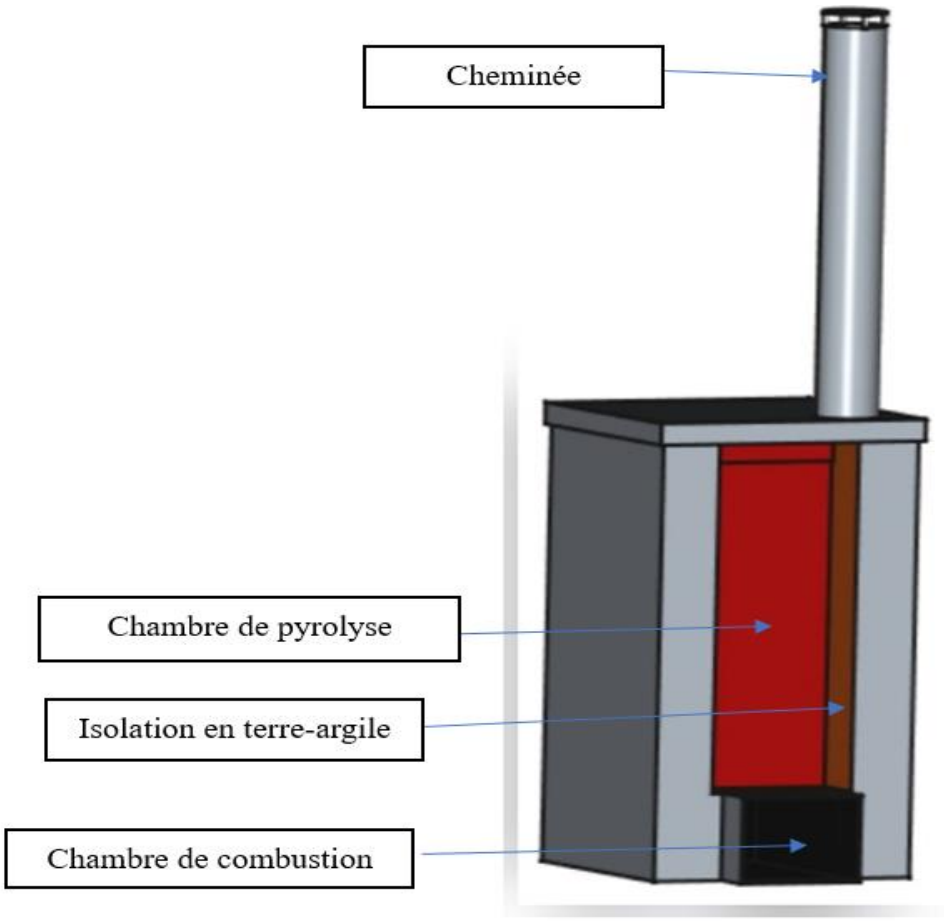
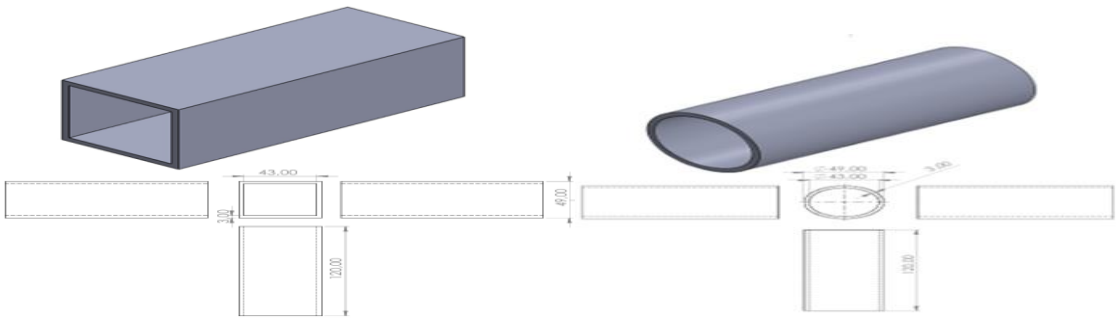


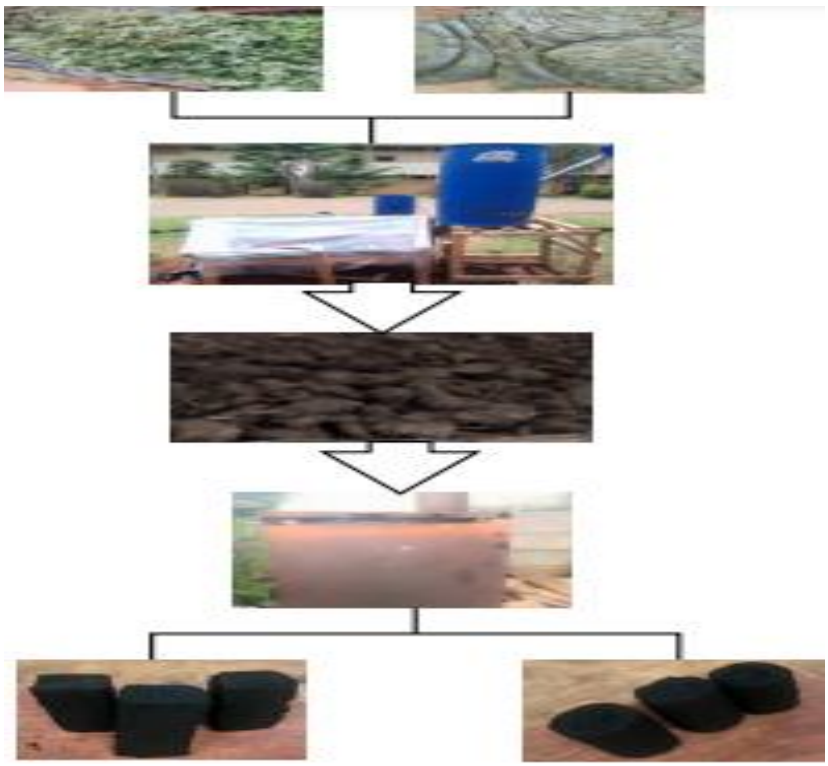

Fig. 1. Pyrolysis reactor and its compartments.

*Briquettes shape design*

The above biochar powder was submitted to two types of shapes, the parallelepiped and the cylindrical. For this purpose, the moulds corresponding to the above shapes were designed and characterized as 4.3 cm × 3.5 cm × 4.3 cm and 4.3 cm diameter for the parallelepiped and the cylindrical shapes, respectively (Figure 2). These dimensions were selected based on previous studies (Tanyi *et al.*, 2023). The biochar was mechanically mixed with a binder made up of cassava flour and water (Rivera *et al.*, 2021) at a ratio of 1:0.05:0.5 in mass (kg). The mixture was introduced into the moulds and then submitted to a mechanical press producing 13 MPa. After demoulding, the obtained shaped briquettes were dried for 24 hours at 22°C in an oven at 105°C (Jama *et al.*, 2000; Bot, 2022) to reach a moisture content of 5%.




a



b

Fig. 2. a) Briquette shape moulds b) Briquettes' production process.

***Characterization of briquettes***

*Physical characterization*

The physical characterization of the briquettes involved measuring their length, width, and thickness. The measurement was done using the digital vernier caliper.

*Chemical characterization*

The chemical characterization consisted of determining the moisture content (MC), the volatile matter (VM), and the fixed carbon content (FCC) given by equations 5, 6, and 7, respectively.

$$H(\%) = \frac{M_{wet} - M_{105°C}}{M_{wet}} \times 100 \quad (5)$$

H(%): Moisture content (%); $M_{wet}$ : Mass of the wet sample (g); $M_{105°C}$ : Mass obtained after heating to 105°C (g)

$$VM(\%) = \frac{M_1 - M_2}{M_1 - M_0} \times 100 \quad (6)$$

$M_0$ : Mass of empty crucible (g); $M_1$ : Mass of crucible with sample before heating (g); $M_2$ : Mass of crucible with sample after heating (g); VM : Volatile matter content (%)

$$FCC(\%) = 100 - (H + VM + ash\ content) \quad (7)$$

*Thermal characterization*

The Briquette thermal characterization was carried out using the lower calorific value (LHV) quantified by equation 8.

$$LHV = \frac{80(100 - ash\ content) \times 4{,}18}{1000} \quad (8)$$

LHV: Lower calorific value (MJ/kg)

The bulk density (ρ) was determined by the ratio between the mass of the briquettes and their geometric volume. This property directly influences handling, storage, and energy density.

***Briquette combustion testing***

To evaluate the thermal performance of the briquettes, 170 g of fuel for both shapes (Parallelepiped and cylindrical) was introduced into a laboratory water-boiling furnace. 1 liter of water was used for both tests. The briquettes were placed in the furnace firebox and ignited with a blowtorch, with an estimated ignition time of 1 minute. A pot of water was then placed on the stove, and the initial water temperature was recorded with a thermocouple. The water temperature was then measured every 10 minutes. The comparative analysis focused on combustion efficiency given by equation 9.

$$Q = mc\Delta T \quad (9)$$

Q : Amount of heat exchanged (J); m : Mass of the body (kg); c : Specific heat capacity ($J.kg^{-1}°C^{-1}$); ΔT : Change in water temperature (°C)

## Results and Discussion

*Pyrolysis process evaluation*

The evolution of pyrolysis temperature over time is shown in Figure 3. The process lasted 10 hours with a final temperature of 390 °C and an average heating rate of 24.6 °C/h. This rate falls within the recommended range for slow pyrolysis (10–50 °C/h), which promotes gradual biomass degradation and better carbon retention (Manyà, 2012).

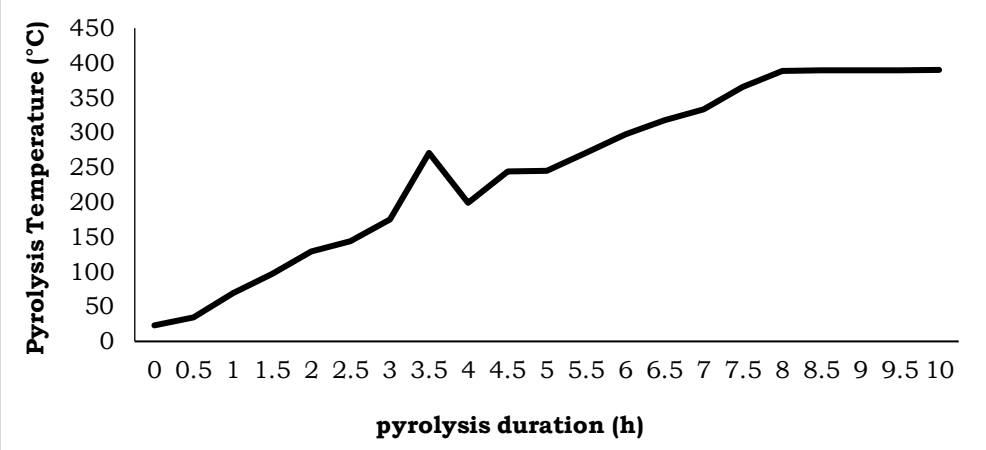



Fig. 3. Evolution of pyrolysis temperature over time.

The temperature readings show an initial moderate increase from 23°C to 129°C during the first two hours, followed by a more rapid rise between 2.5 and 3.5 hours, reaching 270°C. A moderate fluctuation was observed between 3.5 and 5.5 hours, before gradually stabilizing around 390°C between 8 and 10 hours. These variations reflect the heat losses inherent in artisanal kilns, in the absence of fine regulation (Manyà, 2012). The temperature range obtained is consistent with previous studies (Pecchi and Baratieri, 2019). In fact, slow pyrolysis is characterized by a temperature range of 300 to 500°C, yielding solid biochar. It is the same throughout pyrolysis, though the observed time for the temperature rise is slightly higher than in the literature (Lehmann and Joseph, 2015; Alburquerque *et al.*, 2012). The main difference could be related to the pyrolysis reactor performance.

***Physical properties***

The physical properties of the briquettes are presented in Table 1. A slight difference in bulk density is observed between parallelepiped and cylindrical briquettes, with values of 0.487 g/cm³ and 0.4738 g/cm³, respectively.

Table 1. Physical characteristics of briquettes.

| Parameters | Parallelepiped briquettes | Cylindrical briquettes |
|---|---|---|
| Mass (g) | 57.57 | 53.43 |
| Height (cm) | 7.3 | 7.525 |
| Length (cm) | 4.0 | |
| Width (cm) | 3.5 | |
| Diameter (cm) | | 4.3 |
| Volume (cm³) | 118.74 | 112.81 |

This difference can be attributed to the shape of the molds used. In fact, the right angles of the parallelepiped molds promote better distribution of the mixture and more uniform compression during manual pressing, thus limiting the formation of internal voids. This results in a slightly higher density and better mechanical cohesion, as noted by Oladeji (2010), who reports that flat-walled molds tend to produce briquettes with greater mechanical strength than rounded molds.

***Chemical properties***

The chemical properties of the briquettes are presented in Table 2.

Table 2. Chemical characteristics of briquettes.

| Parameters | Parallelepiped briquettes | Cylindrical briquettes |
|---|---|---|
| Apparent density (g/ cm³) | 0,487 | 0,4738 |
| Humidity (%) | 5 | 5 |
| Ash content (%) | 41,8 | 41,8 |
| Taux de carbone fixe (%) | 52,62 | 52,62 |
| Volatile matter content (%) | 0,58 | 0,58 |
| LVH (MJ/kg) | 19,48 | 19,48 |

Chemical parameters such as moisture content (5%), ash (41.8%), fixed carbon (52.62%), volatile matter (0.58%), and lower heating value (19.48 MJ/kg) are identical for both briquette types. This uniformity can be explained by the use of the same raw material (digestate), but this result also shows a homogeneous slow pyrolysis process.

***Combustion temperature evaluation***

Figure 4 below illustrates the variation in water temperature over time for both briquette types. Regardless of briquette shape, combustion temperatures ranged from 19°C to 62°C at 80 minutes.

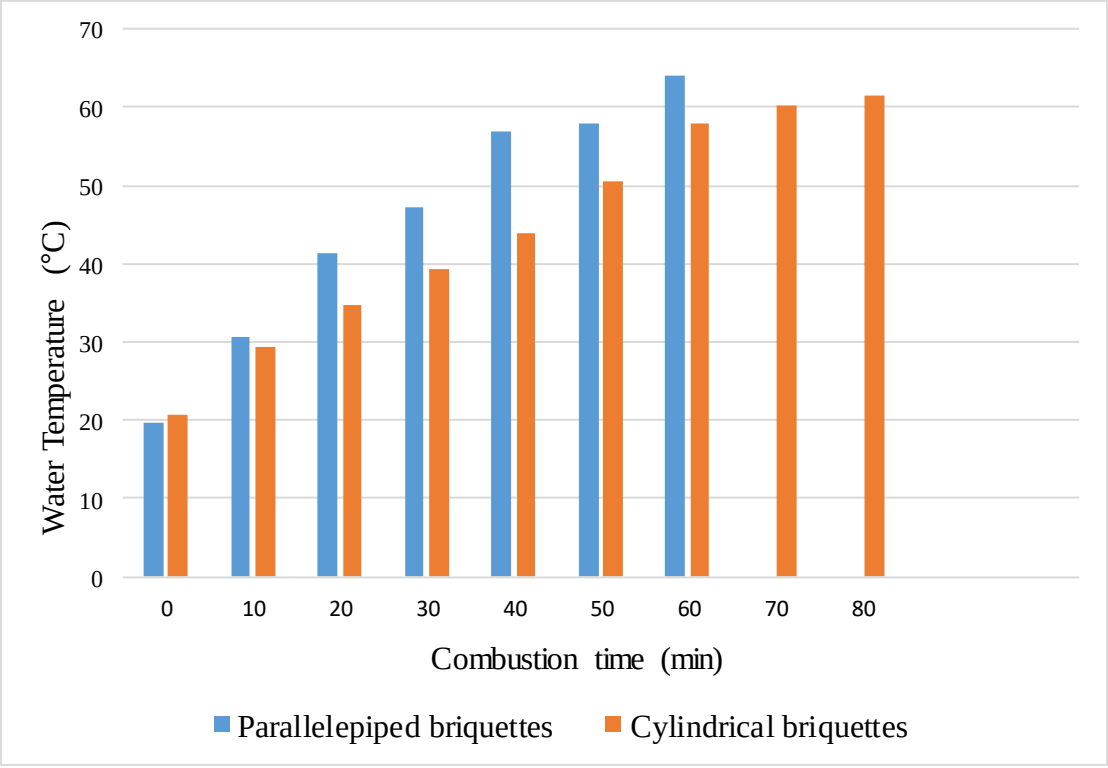



Fig. 4. Evolution of combustion temperature over time for different briquette shapes.

Parallelepiped briquettes achieved the highest combustion temperatures, reaching a maximum of 64°C at 60 minutes, whereas cylindrical briquettes burned much longer, reaching a maximum temperature of 61.6°C at 80 minutes. These results show that the

parallelepiped shape promotes a faster rise in temperature, making it suitable for applications requiring immediate heating, while the cylindrical shape maintains a stable temperature for longer.

***Briquettes mass evolution during combustion***

Table 3 below shows the briquettes' initial and final masses before and after combustion, respectively.

Table 3. Mass variation for different briquettes during combustion.

| Briquettes Shape | Duration (min) | Initial mass (g) | Final mass (g) |
|---|---|---|---|
| parallelepiped | 60 | 170 | 74 |
| Cylindrical | 80 | 170 | 67 |

The loss of mass is greater for parallelepiped briquettes (96 g) than for cylindrical briquettes (103 g), reflecting faster, more concentrated combustion in the former and slower but more complete combustion in the latter (Lange *et al.*, 2018).

***Water mass diminution during combustion***

Table 4 below shows the initial and final water masses before and after combustion, respectively.

Table 4. Water mass variation for different briquettes used as fuel.

| Briquettes Shape | Duration (min) | Initial mass (g) | Final mass (g) |
|---|---|---|---|
| parallelepiped | 60 | 1078 | 1050 |
| Cylindrical | 80 | 1078 | 996 |

Water loss is greater for cylindrical briquettes (82 g) than for parallelepiped briquettes (28 g), a direct consequence of their longer burning time (80 min vs. 60 min). These differences are related to the physical properties induced by the geometry of the briquettes. Parallelepipeds have a higher density (0.487 g/cm³), resulting from stronger compaction, which reduces porosity and limits oxygen circulation (Kaliyan and Morey, 2009). This high density explains their intense, rapid combustion, which releases 0.199 MJ of energy over a shorter period, with limited evaporation.

## Conclusion

This study showed that it is possible to recover digestates from the anaerobic co-digestion of cow manure and Tithonia diversifolia into biochar briquettes that meet domestic energy needs, using a traditional process combining solar drying and slow pyrolysis. The results obtained (calorific value: 19.48 MJ/kg, ash: 41.8%, fixed carbon: 52.62%) indicate acceptable energy performance, with a marked influence of geometric shape: parallelepiped briquettes promote rapid temperature rise and are suitable for instantaneous use, while cylindrical briquettes ensure slower, more prolonged combustion. These results highlight the importance of controlling density, moisture content, and compaction to improve thermal efficiency, while providing a sustainable alternative to fossil fuels and reducing deforestation. Future work should explore optimizing production conditions and conducting a socio-economic evaluation of this technology to promote its large-scale adoption.

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# Multi-environment trial (MET) evaluation of bread wheat (*Triticum aestivum* L.) genotypes across the highlands of Ethiopia using factor analytic mixed models

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**A B S T R A C T**

This study evaluated 37 multi-environment trials (METs) comprising 787 bread wheat genotypes, using Alpha lattice and partially replicated designs across the highland agro-ecological zones of Ethiopia from 2021 to 2024. The study identified significant phenotypic variation, with grain yields ranging from 1.54 to 7.39 t $ha^{-1}$ across environmental trials. The genotypes EBW170049 and EBW170074 appeared as superior performers, yielding 5.31 t $ha^{-1}$ and 5.17 t $ha^{-1}$, respectively, while 65% of the genotypes exceeded the 4.5 t $ha^{-1}$ productivity threshold. The superior performance of EBW170049 was complemented by strong grain quality parameters, with HLW of 70.37 kg $hl^{-1}$ and TKW of 38.46 g, suggesting a stable and efficient grain-filling period. A Factor Analytic Mixed Model (FAMM) captured over 99.9% of the cumulative genetic variance, facilitating a precise decomposition of environmental interactions. Broad-sense heritability reached 99.16% for days to heading and 98.16% for grain yield in high-potential sites, although environmental sensitivity reduced plant height heritability to 52.65% in strained locations. Trait-based environmental clustering helped delineate principal mega-environments and identified specific trial outliers. The finding revealed that early-to-medium maturity demonstrated by superior genotypes serves as a critical terminal stress-escape strategy. Furthermore, top-performing genotypes generally exhibited medium plant height as lodging resistance potential. Regarding biotic stress, genotypes EBW170051 and EBW170058 showed superior yellow rust resistance, while EBW222276 remained resistant to stem rust. Overall, the study confirmed high genetic gain potential and demonstrated that FAMM-based MET analysis is a robust framework for identifying superior genotypes and enhancing productivity and climate resilience in bread wheat breeding programs.

**Keywords:** Factor analytic model, Genotype-by-Environment interaction, Genetic gain, Rust resistance

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## Introduction

Bread wheat (*Triticum aestivum* L.) is a hexaploid cereal (2n = 6x = 42; AABBDD) and the world's most widely grown crop. It accounts for approximately 95% of global wheat production and provides about 20% of the total calories and protein consumed by humans (Anonymous, 2023; Shewry and Hey, 2015). Although there have been significant advancements in wheat productivity, further efforts are required to address the challenge posed by the continued growth of the global population,

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which is projected to reach 9.8 billion by 2050 (Hanafi, 2020). In Ethiopia, wheat is a top-priority food and a strategic crop for national food security and rural livelihoods. Bread wheat now occupies over 90% of the wheat-growing area in Ethiopia, surpassing traditional durum wheat due to improved varieties with higher yield potential and disease resistance (Hodson *et al.*, 2020; Jaleta *et al.*, 2019). It is a significant source of protein, dietary fiber, B vitamins, and minerals (Levy *et al.*, 2020). Beyond its nutritional value, bread wheat is essential for producing various traditional foods, including bread, porridge (genfo), local beer (tela), roasted grain (kolo), boiled grain (nifro), and injera (Geneti *et al.*, 2022; Mullualem *et al.*, 2024). Furthermore, wheat straw is frequently utilized as roofing material and livestock feed, underscoring its socio-economic importance in mixed farming systems (Anteneh *et al.*, 2020). It is cultivated on approximately 2.1 million hectares annually, with 1.7 million hectares under rain-fed conditions and 0.4 million hectares under irrigation (Tadesse *et al.*, 2022). Recently, Ethiopia achieved 100% wheat self-sufficiency with a surplus for export, indicating that the new irrigated wheat initiative has been transformational (Effa *et al.*, 2023). The Ethiopian government continues to enhance production through land expansion, agro-clustering of farmers, and the expansion of irrigation into lowlands (Senbeta and Worku, 2023; Tadesse *et al.*, 2022).

Even though an average wheat yield reached 3.12 t $ha^{-1}$ in 2024, farmers still face a major gap between actual and potential yield in Ethiopia. This gap is attributed to biotic and abiotic stresses, suboptimal agronomic practices, and limited access to technology. Among biotic constraints, rust diseases—particularly stem rust and stripe rust—pose serious threats (Hodson *et al.*, 2020). Ethiopia is among the most important wheat-producing countries and is highly threatened by cereal rusts, particularly yellow and stem rusts. There exist frequent epidemics of these diseases as a result of the evolution of new races. Regardless of the enormous efforts to develop high-yielding, disease-resistant varieties, the agronomic life span of most varieties is very short. Current commercial bread wheat varieties cultivated in the highlands are susceptible to stem rust and have a long maturity period (Senbeta and Worku, 2023). Therefore, developing a new rust-resistant, high-yielding, and early-maturing variety is a paramount solution for resource-poor farmers growing wheat in Ethiopia's highlands. To address these challenges, breeding programs focus on developing high-yielding and rust-resistant varieties. However, genotype-by-environment (G×E) interaction complicates the identification of superior genotypes (Zhao *et al.*, 2025). Therefore, Multi-environment trials (METs) are essential for evaluating genotypes across diverse agro-ecologies and identifying adapted varieties (Waters *et al.*, 2023). Linear mixed models, particularly factor analytic mixed models (FAMM), provide a robust framework for MET analysis by capturing G×E covariance structures (Argaw and Demelash, 2025; Smith *et al.*, 2001).

Furthermore, factor analytic mixed models (FAMM), which incorporate spatial analysis, account for field heterogeneity and enhance selection precision (Alemayehu *et al.*, 2025; Argaw *et al.*, 2024). Importantly, combining FA models with spatial models for non-genetic effects greatly improves the analysis of MET datasets, as demonstrated in related studies by Cullis *et al.* (2010) and Kelly *et al.* (2007). FA models are useful not only for accurately estimating and predicting genetic effects but also for estimating their variance and conducting graphical analyses (Smith *et al.*, 2001). By utilizing estimated genetic variance, breeders can identify correlated environments and select genotypes based on best linear unbiased predictions (BLUPs) averaged across these environments (Argaw *et al.*, 2024). Understanding the variance structure related to genotype-by-environment effects is a crucial component of the FA model for METs. The present research was conducted to evaluate the performance of bread wheat genotypes that may be suitable for the diverse agro-ecological conditions of Ethiopia, employing more efficient statistical methods for data analysis. Thus, this study aims to enhance selection strategies in bread wheat breeding by analyzing MET data using a FAMM-based approach to evaluate bread wheat genotypes across the major highland wheat-growing regions of Ethiopia. Hence, the objectives of this study were to evaluate the performance, disease resistance, and stability of bread wheat genotypes across diverse highland environments in Ethiopia using more advanced statistical models.

## Materials and Methods

### *Dataset*

The MET datasets were compiled from four trial categories: Observation Nursery (ON; 2021–2022), Preliminary Variety Trials (PVT; 2021–2022), National Variety Trials Stage-I (NVT1; 2022–2023), and National Variety Trials Stage-II (NVT2; 2022–2024), while the NVT trials cover a broader range of environments (Table 1). These trials were conducted across nine representative locations within major high-rainfall bread wheat-growing regions, with Debreziet and Meraro serving specifically as disease screening sites.

A total of 787 unique genotypes, including 2 checks, were evaluated across 37 trial–location–season combinations. For the combined Observation Nursery, Preliminary Variety Trials, and NVT Stage-I (OPN) trials, a partially replicated design was used to accommodate a large number of genotypes while maintaining precision in early-stage evaluations (Piepho *et al.*, 2021). OV, PVT and NVT trials were arranged in row–column alpha lattice designs to account for spatial variability within the field (Butler and Cullis, 2022).

Table 1. Detailed agro-ecological and weather descriptions of the testing location.

| Location | Code | Altitude (m) | Latitude | Longitude | Mean Temp. | | Mean Rainfall(mm) |
|---|---|---|---|---|---|---|---|
| | | | | | Min. | Max. | |
| Kulumsa | KU | 2200 | 08°01'10"N | 39°09'11"E | 10.5 | 22.8 | 820 |
| Bekoji | BE | 2780 | 07°32'37"N | 39◦15'21"E | 7.9 | 18.6 | 1010 |
| Koffele | KF | 2695 | 07°00′00"N | 38°45′00"E | 8.6 | 19.7 | 1170 |
| Enawari | EW | 2650 | 09°53'00"N | 39°09'00"E | 15.0 | 20.0 | 878 |
| Arsi Robe | RA | 2420 | 07°53'02"N | 39°37'40"E | 6.0 | 22.1 | 796 |
| Debre Markos | DM | 2450 | 10°19′59″N | 37°44′53″E | 12.4 | 23.5 | 1300 |
| Holletta | HL | 2400 | 09°03′41″N | 38°30′44″E | 6.1 | 22.4 | 1100 |
| Chefe Donsa | CD | 2444 | 08°57′60″N | 39°06′28″E | 9.8 | 23.1 | 1100 |
| Gonder | GD | 2,133 | 12°36'00"N | 37°28'00"E | 12.3 | 26.7 | 937 |
| Debre Zeit | DZ | 2050 | 08°38'08"N | 38°30'15"E | 11.4 | 26.8 | 985 |
| Meraro | MR | 3,030 | 07°24'00"N | 39°14'00"E | 10.0 | 17.0 | 1200 |

### *Data collection*

Data were recorded on days to heading, plant height, thousand-kernel weight, hectoliter weight, and grain yield. The description of the collected data/traits has been shown as follows:

*Days to Heading (DTH):* Obtained by recording days from the sowing date to when 75% of spikes have fully emerged.

*Plant Height (cm):* Measured by averaging the height of five random plants from the ground to the spike tip (excluding awns) after physiological maturity.

*Thousand Kernel Weight (g):* Determined by counting the seeds with a seed counter and weighing them on a sensitive balance at 12.5% moisture content.

*Hectoliter Weight (kg hl$^{-1}$):* Measured as the flour density (kg hl$^{-1}$) produced from a hectoliter of seed after harvest using a specialized grain analyzer.

*Grain Yield (t ha$^{-1}$):* Grain yield in grams was obtained from the entire plots harvested after physiological maturity, weighed, and converted to tons per hectare at 12.5% moisture content.

### *Trial designation*

Table 2 summarizes the 37 Trials, including trial design and trait measurements. Each trial was identified by a name (e.g., 21BWOLBE) combining the last two digits of the trial year (21= 2021), two letters of the crop under study (BW = Bread Wheat), the first letters of the trial series (OL = Observation nursery for Late maturity), and the testing site/location code (BE = Bekoji). Table 2 also provides the number of replications, the dimensions of each trial (rows × columns), and the average trait values across trials. In this study, the terms "environment" and "trial/site" are used interchangeably.

Table 2. Summary of trial scheme and average trait measurements across trials.

| Trial | No. of Reps | No. of Rows | No. of Columns | No. of Genotypes | Average measurement | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | GYLD | PHT | HLW | DTH | TKW |
| 21BWOLBE | 2 | 30 | 10 | 200 | 1.54 | 93.83 | 59.54 | 82.47 | 24.95 |
| 21BWOLKF | 2 | 30 | 10 | 200 | 1.66 | 89.78 | 52.81 | 78.87 | 26.10 |
| 21BWPLBE | 3 | 26 | 10 | 127 | 2.18 | 91.35 | 62.11 | 80.32 | 26.99 |
| 21BWPLKF | 3 | 26 | 10 | 127 | 2.29 | 86.00 | 57.01 | NA | 29.57 |
| 22BWNLBE | 3 | 15 | 10 | 50 | 3.65 | 92.4 | 68.80 | 81.83 | 38.29 |
| 22BWNLCD | 3 | 15 | 10 | 50 | 5.20 | 86.23 | 72.21 | 71.29 | 50.86 |
| 22BWNLDM | 3 | 15 | 10 | 50 | 4.69 | 94.62 | NA | 67.00 | 47.75 |
| 22BWNLEW | 3 | 15 | 10 | 50 | 6.99 | 90.70 | 83.60 | 78.83 | NA |
| 22BWNLGD | 3 | 15 | 10 | 50 | 4.92 | 94.03 | NA | 72.21 | 41.43 |
| 22BWNLHL | 3 | 15 | 10 | 50 | 2.97 | 88.55 | 74.02 | 63.87 | 30.99 |
| 22BWNLKF | 3 | 15 | 10 | 50 | 3.17 | 91.05 | 58.71 | NA | NA |
| 22BWNLKU | 3 | 15 | 10 | 50 | 5.02 | 93.19 | 63.62 | 62.27 | 35.39 |
| 22BWNLRA | 3 | 15 | 10 | 50 | 5.15 | 93.89 | 70.77 | 68.35 | 44.81 |
| 22BWOLBE | 2 | 30 | 10 | 200 | 2.42 | 103.46 | 62.35 | 83.61 | 32.71 |
| 22BWOLKF | 2 | 30 | 10 | 200 | 2.20 | 99.55 | 55.68 | NA | 26.26 |
| 22BWPLBE | 3 | 28 | 8 | 112 | 2.83 | 91.30 | 67.78 | 81.79 | 33.66 |
| 22BWPLDM | 3 | 28 | 8 | 112 | 4.26 | 96.90 | NA | 69.24 | NA |
| 22BWPLEW | 3 | 28 | 8 | 112 | 7.39 | 93.37 | 81.96 | 81.07 | 49.29 |
| 22BWPLHL | 3 | 28 | 8 | 112 | 2.55 | 88.33 | 74.77 | 64.98 | 29.72 |
| 22BWPLKU | 3 | 28 | 8 | 112 | 4.63 | 97.21 | 61.55 | 63.90 | 27.62 |
| 22BWPLRA | 3 | 28 | 8 | 112 | 4.07 | 90.21 | 69.57 | 71.24 | 43.24 |
| 23BWNLBE | 3 | 10 | 9 | 30 | 4.15 | 85.26 | 72.15 | 83.84 | 43.16 |
| 23BWNLDM | 3 | 10 | 9 | 30 | 5.15 | 85.70 | NA | 66.10 | NA |
| 23BWNLHL | 3 | 10 | 9 | 30 | 4.62 | 90.14 | NA | 62.63 | 41.49 |
| 23BWNLRA | 3 | 10 | 9 | 30 | 2.89 | 87.58 | 67.14 | 65.48 | 33.07 |
| 23BWOPNLKU | 3 | 42 | 13 | 325 | 3.67 | 86.92 | 64.96 | 67.02 | 32.51 |
| 23BWPLBE | 3 | 14 | 12 | 84 | 2.79 | 87.85 | 69.45 | 85.83 | 39.31 |
| 23BWPLDM | 3 | 14 | 12 | 84 | 3.61 | 90.12 | NA | 64.23 | NA |
| 23BWPLHL | 3 | 14 | 12 | 84 | 4.19 | 88.02 | NA | 62.09 | 39.55 |
| 23BWPLRA | 3 | 14 | 12 | 84 | 2.53 | 94.88 | 66.79 | 65.00 | 33.60 |
| 24BWOPNLBE | 3 | 35 | 9 | 169 | 2.84 | 87.49 | 59.70 | 82.30 | 28.84 |
| 24BWOPNLKU | 3 | 35 | 9 | 169 | 4.74 | 102.55 | 66.00 | 72.95 | 27.38 |

*GYLD= Gain yield, PHT=Plant height, DTH= Days to heading, TKW=Thousand kernel weight, HLW = Hectoliter weight, NA= Not available, O = Observation nursery, L= Late maturity groups, P = Preliminary variety trails, N= National variety trails*

### *Statistical analysis*

The Multi-Environment Trial (MET) analysis was performed for trials evaluated at high-altitude areas of Ethiopia during the 2021 to 2024 cropping seasons. Genetic variance, error variance, heritability, and clustering across trials were analyzed using advanced statistical approaches, including Factor-analytic mixed models and genotype-by-environment interaction, implemented in ASReml and the Metan R package (Olivoto *et al.*, 2023)**.** The ASReml-R statistical software package was used to fit all models analyzed in this study (Butler *et. al.*, 2009).

## Results and Discussion

### *Mean performances of genotypes across environments*

A comprehensive analysis of 37 trials conducted during the 2021 to 2024 main cropping season revealed a significant phenotypic range across all traits (Table 2). Using a Factor Analytic Mixed Model (FAMM) to evaluate bread wheat genotypes enabled precise modeling of G×E interactions and spatial variability, facilitating the identification of stable, high-performing genotypes (Smith *et al.*, 2001; Argaw and Demelash, 2025). The mean grain yield (GYLD) across the study sites was 3.78 t ha$^{-1}$; this average masked a nearly five-fold discrepancy between the lowest-yielding trial, 21BWOLBE (1.54 t ha$^{-1}$), and the highest, 22BWPLEW (7.39 t ha$^{-1}$). Such fluctuations in mean yield are frequently attributed to varying moisture availability and heat stress during the critical flowering stage (Mondal *et al.*, 2020), a trend reflected in the lower performance of the 2021 trial series compared to the 2022 and 2023 cohorts. Grain yield varied significantly across genotypes, ranging from

2.39 t ha$^{-1}$ to 5.47 t ha$^{-1}$, with EBW170049 (5.31 t ha$^{-1}$) and EBW170074 (5.17 t ha$^{-1}$) as the top performers, followed closely by elite genotypes EBW222923 (5.06 t ha$^{-1}$) and EBW170051 (5.03 t ha$^{-1}$). Such a vast gap suggested that the yield potential was profoundly influenced by localized environmental factors or Genotype by Environment (G × E) interactions. The grain yield results were further elucidated by grain quality parameters, with Hectoliter Weight (HLW) averaging 66.52 kg hL$^{-1}$ and Thousand Kernel Weight (TKW) averaging 35.50 g. The significant range—from 24.95 g (21BWOLBE site) to 50.86 g (22BWNLCD site) for TKW—directly reflects the observed trends in total grain yield. As grain weight is a primary determinant of cereal yield potential (Slafer *et al.*, 2022), the higher performance of genotypes at the 22BWNLCD site highlights the critical role of grain density in driving overall productivity.

Structural and phenological traits also exhibited distinct environmental patterns. Significant variation was observed among genotypes, with DTH ranging from 67.78 to 80.12 days and PHT varying from 85.67 to 105.1 cm, suggesting a heterogeneous genetic background for height-reduction genes. This implied that Plant Height (PHT) remained relatively stable with a mean of 91.64 cm, while Days to Heading (DTH) showed a substantial 24-day gap between the earliest and latest trial sites. Hence, optimizing the heading date is essential for escaping terminal stress (Tadesse *et al.*, 2021), suggesting that trials reaching the 72-day mean likely benefited from a more favorable grain-filling gap than those with extreme early or late maturity. The majority of high-yielding genotypes headed between 69 and 72 days, identifying early-to-medium maturity as a key adaptive trait. The early heading recorded for genotypes such as EBW212354 (67.78 days) and EBW212116 (69.03 days) represented a "terminal stress escape" strategy, which allowed the crop to complete anthesis before the onset of frost and the rapid depletion of residual soil moisture common in the highland areas of Ethiopia. Furthermore, the dominance of semi-dwarf types (90–95 cm) among high-yielding lines, such as EBW170074, reflected an optimized Harvest Index (HI). While ultra-short plants may lack carbohydrate storage capacity, taller genotypes often prioritize vegetative biomass over reproductive sinks, explaining their lower yield performance (Xue *et al.*, 2022).

In general, the identification of a "high-yield, early-maturity" bread wheat genotypes—specifically EBW170049, EBW170074, EBW212401, EBW212116, and EBW212354—provided a robust strategy for highland conditions, where frost, low temperatures, and high rainfall limit the growing season. These genotypes reached yields above 4.5 t ha$^{-1}$ by demonstrating enhanced cold tolerance during flowering and optimized biomass accumulation under low-temperature conditions (Xue *et al.*, 2022). Quality parameters further supported these findings, as EBW212354 recorded the highest TKW (45.58 g). Ultimately, the superior performance of these elite genotypes confirmed that high kernel weight, hectoliter weight (HLW), and optimized plant height were the primary drivers of genetic gain. Consequently, this study demonstrated that incorporating FAMM effectively partitioned genetic and environmental variance, thereby pinpointing superior bread wheat germplasm. These results provided valuable resources for breeding programs aimed at enhancing climate resilience and yield stability in the rain-fed highlands of Ethiopia.

***Variance components and heritability estimates for each trait***

Estimates of genetic variance, error variance, and heritability for each trait across trials are presented in Table 3. Understanding variance components and heritability is essential for effective selection in plant breeding (Cullis *et al.*, 2010). These metrics provided insights into the potential response to selection for the key traits measured across the highland rain-fed areas of Ethiopia. Hence, the evaluation of Bread wheat genotypes across multiple highland areas revealed a substantial range of genotypic variance, a fundamental requirement for any successful breeding program. In almost all environments, the genetic variance for grain yield (GYLD) was significantly higher than the environmental variance. Grain yield is a typical polygenic trait, yet the data revealed an unexpectedly robust genetic architecture across the tested environments. This suggested the presence of stable genetic markers that could be highly valuable for developing crops that perform reliably in different climates. Hence, genetic variance for Grain Yield fluctuated significantly, peaking at 3.78 in the 22BWNLKF environment, while the corresponding error variance remained

negligible at 0.22, resulting in a high broad-sense heritability of 98.16%, indicating that in specific high-potential highland environments, the genetic signal for yield was highly detectable. Conversely, in more restrictive environments like 22BWPLEW, heritability dipped to 68.45%, with error variance (0.53) exceeding genetic variance (0.34). Recent literature emphasizes that, while yield is highly influenced by Genotype × Environment interactions, the high heritability observed in many Ethiopian wheat-growing sites indicates that substantial genetic gains could still be achieved through direct selection (Tadesse *et al.*, 2022). Furthermore, integrating genomic selection and high-throughput phenotyping can accelerate these gains by more effectively accounting for complex Genotype × Environment interactions than traditional methods alone (Merrick *et al.*, 2022).

The phenological development of the crop, represented by days to heading, showed the most consistent and highest heritability estimates across all trials, frequently exceeding 95% (e.g., 99.16% at the 23BWNLHL site). The genetic variance values for days to heading were substantially larger than their error variance counterparts in nearly every instance, indicating that time to flowering is under strict genetic control and minimally susceptible to minor environmental fluctuations common in highland agro-ecologies. In the context of contemporary climate-resilient breeding, the high heritability of days to heading enables breeders to precisely select maturity groups that align with specific rainfall patterns in the highlands (Mwadzingeni *et al.*, 2021). Furthermore, plant height exhibited a wide range of genetic variance, reaching as high as 89.39 at the 22BWOLKF site. While heritability remained generally high (averaging between 80% and 95%), there were notable exceptions, such as 22BWPLDM, where heritability fell to 52.65%. In this specific case, the error variance (19.75) was nearly quadruple the genetic variance (5.07), indicating that environmental factors unique to certain highland sites—such as soil fertility gradients, high-altitude moisture availability, or plant competition—significantly influenced stem elongation. Moreover, modern wheat breeding prioritizes semi-dwarf architectures to improve harvest index and lodging resistance, which is vital in high-input highland systems. Similarly, recent findings have shown that high heritability of morphological traits facilitates selection for optimal biomass distribution, enabling the development of varieties that can support high grain loads without lodging, even under high-input conditions (Voss-Fels *et al.*, 2019).

On the other hand, the traits associated with grain physical quality, such as thousand-kernel weight (TKW) and hectoliter weight (HLW), exhibited high genetic variance relative to environmental variance, with heritability often exceeding 90%. The high heritability for TKW was recorded at the 21BWPLBE site (94.06%), driven by a genetic variance of 30.47 against a low error variance of 4.99. Likewise, HLW followed a similar trend, showing higher heritability across most highland sites with 97.49% at 22BWNLHL site. This indicated that the density and size of bread wheat grain are primarily determined by the varieties' inherent genetic makeup rather than by site-specific soil or weather conditions. Recent global meta-analyses of wheat quality noted that TKW and HLW are critical components of both milling yield and market value (Guzmán *et al.*, 2022). Therefore, the high heritability values found in this dataset implied that these traits are less sensitive to Genotype × Environment interactions than grain yield itself. Consequently, selection for high TKW and HLW can be conducted with high confidence across diverse highland environments, providing a reliable pathway to improve the overall yield performance of bread wheat genotypes in Ethiopia.

Overall, specific highland locations, such as 24BWOPNLBE and 22BWNLHL, appeared to be "gold standard" environments for selection because they consistently provided the ideal balance of high genetic variance and high heritability. Hence, optimal selection environments demonstrated high genetic variance and low environmental error, supporting the advancement of climate-resilient cultivars. These superior environments maximize the potential for genetic gain by ensuring that selection pressure was applied to phenotypic differences that are almost entirely attributable to the underlying genotype rather than environmental noise (Cullis *et al.*, 2010). By prioritizing genotypes that excel at these high-potential highland sites, breeders can capture the highest possible gains for both grain yield and quality traits

in a single selection cycle. Generally, Multi-environment trials across the Ethiopian highlands revealed high heritability for grain yield, days to heading, and grain quality, enabling effective selection of bread wheat genotypes. Therefore, the overall trend across the 37 highland site-year combinations confirmed that most of the genotypes under study possessed high genetic gain potential, establishing them as excellent candidates for promotion to advanced variety trials across the highlands of Ethiopia.

Table 3. Estimates of genetic variance, error variance and heritability for each trait across trials.

| Site | GYD | | | DTH | | | PHT | | | TKW | | | HLW | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Gvar | Evar | $H^2$ | Gvar | Evar | $H^2$ | Gvar | Evar | $H^2$ | Gvar | Evar | $H^2$ | Gvar | Evar | $H^2$ |
| 21BWOLBE | 0.93 | 0.04 | 97.03 | 7.62 | 1.06 | 94.75 | 17.99 | 19.75 | 68.75 | 41.44 | 6.73 | 91.89 | 29.20 | 3.08 | 83.67 |
| 21BWOLKF | 1.54 | 0.46 | 90.80 | 11.47 | 1.21 | 94.83 | 18.99 | 25.55 | 66.12 | 35.15 | 28.32 | 85.12 | 26.95 | 13.44 | 75.46 |
| 21BWPLBE | 1.10 | 0.08 | 97.62 | 10.63 | 0.76 | 96.83 | 20.91 | 23.43 | 75.62 | 30.47 | 4.99 | 94.06 | 14.14 | 3.62 | 90.15 |
| 21BWPLKF | 1.74 | 0.64 | 92.74 | NA | NA | NA | 26.89 | 45.58 | 69.56 | 41.59 | 12.67 | 91.81 | 24.86 | 9.08 | 89.21 |
| 22BWNLBE | 0.65 | 0.39 | 91.93 | 6.17 | 1.09 | 96.07 | 23.23 | 24.61 | 95.34 | 20.83 | 9.03 | 92.67 | 6.69 | 4.86 | 89.34 |
| 22BWNLCD | 0.08 | 0.48 | 74.36 | 12.86 | 1.57 | 98.14 | 20.95 | 18.79 | 87.23 | 14.24 | 5.24 | 94.24 | 0.43 | 0.51 | 88.26 |
| 22BWNLDM | 0.75 | 0.51 | 91.76 | 12.02 | 1.55 | 99.13 | 18.76 | 9.49 | 97.14 | NA | N A | NA | NA | NA | NA |
| 22BWNLEW | 0.13 | 0.36 | 83.90 | 7.80 | 1.80 | 96.10 | 15.30 | 8.15 | 91.93 | 9.39 | 11.41 | 90.87 | 1.65 | 0.66 | 92.03 |
| 22BWNLGD | 0.26 | 0.44 | 85.16 | 17.77 | 2.50 | 98.16 | 10.40 | 6.58 | 96.78 | 20.80 | 6.97 | 94.57 | 20.29 | 3.05 | 95.87 |
| 22BWNLHL | 0.60 | 0.18 | 94.30 | 24.51 | 2.47 | 98.43 | 18.60 | 12.83 | 96.64 | 35.16 | 4.32 | 96.74 | 48.23 | 5.46 | 97.49 |
| 22BWNLKF | 3.78 | 0.22 | 98.16 | NA | N A | NA | 21.53 | 25.44 | 89.43 | NA | N A | NA | NA | NA | NA |
| 22BWNLKU | 0.80 | 0.39 | 92.28 | 11.39 | 1.62 | 97.31 | 21.49 | 14.34 | 93.33 | 14.85 | 9.39 | 92.94 | 7.29 | 4.44 | 92.57 |
| 22BWNLRA | 1.04 | 0.25 | 94.55 | 28.38 | 4.56 | 96.98 | 20.81 | 21.43 | 97.15 | 21.87 | 4.16 | 94.82 | 3.72 | 1.38 | 92.55 |
| 22BWOLBE | 1.41 | 0.19 | 92.38 | 19.58 | 1.58 | 94.46 | 61.79 | 62.25 | 83.55 | 30.09 | 11.52 | 85.67 | 27.91 | 6.29 | 88.58 |
| 22BWOLKF | 2.26 | 0.16 | 95.60 | NA | N A | NA | 89.39 | 25.15 | 88.12 | 36.56 | 15.52 | 83.97 | 39.70 | 9.07 | 87.56 |
| 22BWPLBE | 0.45 | 0.25 | 87.59 | 8.42 | 1.50 | 93.51 | 13.37 | 15.67 | 71.51 | 14.62 | 11.44 | 85.77 | 8.88 | 5.13 | 87.94 |
| 22BWPLDM | 0.60 | 0.42 | 89.32 | 12.80 | 2.30 | 96.83 | 5.07 | 19.75 | 52.65 | NA | N A | NA | NA | NA | NA |
| 22BWPLEW | 0.34 | 0.53 | 68.45 | 15.31 | 2.58 | 96.20 | 10.36 | 7.07 | 80.78 | 8.17 | 9.58 | 71.55 | 3.19 | 0.54 | 92.15 |
| 22BWPLHL | 0.29 | 0.10 | 91.04 | 28.28 | 1.82 | 98.38 | 11.16 | 17.93 | 86.00 | 23.80 | 5.08 | 92.00 | 12.76 | 2.90 | 91.54 |
| 22BWPLKU | 1.36 | 0.30 | 91.57 | 19.38 | 2.49 | 97.02 | 19.30 | 21.01 | 83.99 | 29.29 | 8.14 | 90.87 | 13.26 | 5.95 | 88.20 |
| 22BWPLRA | 1.35 | 0.36 | 90.65 | 20.56 | 6.68 | 94.34 | 12.06 | 25.30 | 78.54 | 29.26 | 9.06 | 89.59 | 8.25 | 3.66 | 84.83 |
| 23BWNLBE | 0.76 | 0.20 | 94.74 | 2.33 | 0.65 | 96.84 | 19.17 | 17.49 | 87.65 | 26.66 | 6.22 | 95.00 | 9.51 | 1.60 | 96.93 |
| 23BWNLDM | 0.21 | 0.55 | 87.00 | 2.93 | 1.08 | 97.89 | 8.54 | 43.74 | 93.04 | NA | N A | NA | NA | NA | NA |
| 23BWNLHL | 0.15 | 0.21 | 89.98 | 12.79 | 0.52 | 99.16 | 29.65 | 9.74 | 96.75 | 9.52 | 4.25 | 93.78 | NA | N A | NA |
| 23BWNLRA | 0.45 | 0.23 | 94.74 | 14.78 | 1.37 | 98.46 | 23.12 | 29.87 | 93.24 | 34.35 | 7.83 | 94.44 | 18.89 | 4.28 | 95.15 |
| 23BWOPNLKU | 0.80 | 0.61 | 76.45 | 52.44 | 3.29 | 96.70 | 57.88 | 34.20 | 83.50 | 16.02 | 8.18 | 77.92 | 6.02 | 1.76 | 83.36 |
| 23BWPLBE | 0.85 | 0.37 | 90.48 | 1.48 | 0.84 | 91.05 | 62.06 | 19.10 | 94.18 | 35.23 | 6.53 | 94.14 | 18.63 | 2.56 | 96.04 |
| 23BWPLDM | 0.40 | 0.44 | 76.12 | 3.77 | 2.43 | 89.96 | NA | N A | NA | NA | NA | NA | NA | NA | NA |
| 23BWPLHL | 0.34 | 0.25 | 85.16 | 13.29 | 1.01 | 97.39 | 80.93 | 14.67 | 96.26 | 12.32 | 7.60 | 83.80 | NA | N A | NA |
| 23BWPLRA | 0.47 | 0.36 | 87.86 | 17.24 | 1.34 | 97.28 | 48.76 | 32.04 | 89.07 | 15.13 | 11.24 | 80.56 | 9.33 | 3.71 | 89.10 |
| 24BWOPNLBE | 2.04 | 0.19 | 94.63 | 17.26 | 0.90 | 97.00 | 66.60 | 23.16 | 88.37 | 54.74 | 5.38 | 94.13 | 72.99 | 10.17 | 89.30 |
| 24BWOPNLKU | 1.00 | 0.33 | 84.89 | 35.15 | 2.12 | 96.78 | 55.89 | 24.64 | 87.93 | 17.64 | 7.59 | 82.01 | 12.87 | 3.50 | 88.01 |
| 24BWPNLDM | 0.23 | 0.26 | 82.41 | 6.38 | 0.86 | 97.99 | 52.01 | 13.09 | 97.16 | NA | N A | NA | NA | NA | NA |
| 24BWPNLHL | 0.27 | 0.16 | 88.39 | 19.14 | 1.47 | 98.15 | 53.09 | 20.13 | 95.76 | 16.44 | 5.38 | 92.23 | 4.75 | 2.96 | 90.28 |
| 24BWPNLRA | 0.59 | 1.17 | 79.61 | 19.19 | 2.06 | 97.66 | 68.79 | 30.58 | 97.58 | 17.84 | 12.88 | 89.95 | 1.83 | 3.56 | 88.06 |
| 23BWOLBE | NA | N A | NA | 11.54 | 1.60 | 95.03 | 42.14 | 25.86 | 82.86 | 41.68 | 7.04 | 88.33 | 24.45 | 3.40 | 87.52 |
| 23BWOLDM | NA | N A | NA | 24.84 | 8.31 | 95.60 | 28.17 | 16.13 | 84.10 | NA | N A | NA | NA | NA | NA |

*GYLD = Grain Yield, TKW = Thousand kernel weight, HLW = Hectoliter Weight, PHT= Plant height, DTH = Days to Heading, Gvar = Genetic variance, Evar = Error variance and $H^2$=Heritability*

***Genetic correlations and trait-based environmental clustering***

The implementation of Factor Analytic (FA) models and hierarchical clustering facilitated a robust partitioning of the Genotype by Environment (G×E) setting within the high-altitude wheat-growing regions of Ethiopia. Dendrograms based on the dissimilarity matrices derived from the final FA models illustrated that environmental complexity was inherently trait-dependent (Fig. 1). Based on the Dendrograms, 9 distinct groups developed for grain yield (GYLD), while four were identified for hectoliter weight (HLW), three for thousand kernel weight (TKW), and two each for days to heading (DTH) and plant height (PHT). These groupings represented sets of correlated environments in which genotype performance was relatively consistent within each cluster, allowing accurate ranking of genotypes based on Best Linear Unbiased Prediction (BLUP) values.

The hierarchical clustering for grain yield revealed a significant spatial contrast within the testing network. At a 0.4 threshold, the environments partitioned into nine distinct clusters, reflecting the high spatial

variability of Ethiopia's high-altitude regions. A critical finding was the consistent isolation of the Enawari environment (22BWPLEW), which appeared as a standalone outlier at the highest dissimilarity level (~0.8), representing a unique ecological niche. On the other hand, major environments such as Bekoji (21BWOLBE, 24BWPNLBE) and Kulumsa (22BWPLKU) showed strong genetic associations despite their altitudinal gradient (2780 m vs. 2200 m), whereas the unique temperature-moisture regime at the Enawari site induced a distinct physiological response. This isolation underscored the necessity of a specific adaptation-breeding strategy for the Enawari highlands to avoid the masking effect of average performance in more consistent Arsi-zone sites like Arsi-Robe (22BWNLRA).

For phenological and growth traits, the analysis revealed a substantial temporal shift between the 2021–2023 baseline and the 2024 cropping season. The high Agglomerative Coefficients (0.89 for Plant Height and 0.90 for Days to Heading) indicated a highly structured dataset where the 2024 groups formed a distinct "out-group." According to Jenks (2025) and Boyko and Tkachyk (2023), the tight clustering of the 2021–2023 samples (merge heights below 0.2) suggested a period of relative environmental stability. The 2024 environments were isolated at a dissimilarity height of 0.69, suggesting a major climatic or unconditional shift likely resulted from varying rainfall patterns in the Ethiopian highlands. Such "temporal G×E" highlighted the importance of multi-year testing to ensure that phenological stability and lodging resistance were maintained under shifting climatic cycles (Bruzzese and Vistocco, 2025). Moreover, the analysis of Thousand Kernel Weight (TKW) and Hectoliter Weight (HLW) reinforced the vigorous clustering patterns, with Agglomerative Coefficients of 0.81 and 0.84, respectively. While the core environments of the Arsi highlands formed cohesive groups, Enawari (22BWPLEW) was again identified as the primary outlier, merging with the rest of the dataset only at maximum dissimilarity levels (0.78 for TKW and 0.80 for HLW). As discussed by Bruzzese and Vistocco (2025), this "outgroup" status for Enawari underscored a fundamental divergence in grain-filling conditions. The specific higher altitude-rainfall combination at 2650 m potentially extended the grain-filling duration, which fundamentally distinguished its study population from relatively high altitude sites. Supported by the evolutionary visualization frameworks of Müller *et al.* (2024), these findings ensured that regional breeding partitions were grounded in the landscape's inherent mathematical and ecological realities. Consequently, genotypes with superior "stay-green" traits showed specific adaptation to the Enawari niche, whereas they were penalized in environments where terminal stresses were more predominant.

The structural contradiction identified across all traits provided a clear statistical basis for re-evaluating wheat breeding sub-zones in Ethiopia. The high genetic diversity observed between the outlying Enawari cluster and the central Arsi-zone clusters offered a strategic opportunity to design a breeding program that can enhance the production and productivity of bread wheat in high-altitude areas of the country. By identifying these natural divisions without pre-specifying cluster counts, this study ensured that the resulting partitions reflected the data's inherent biological relationships, facilitating the selection of genotypes precisely tailored to the diverse high-altitude agro-ecologies of Ethiopia.

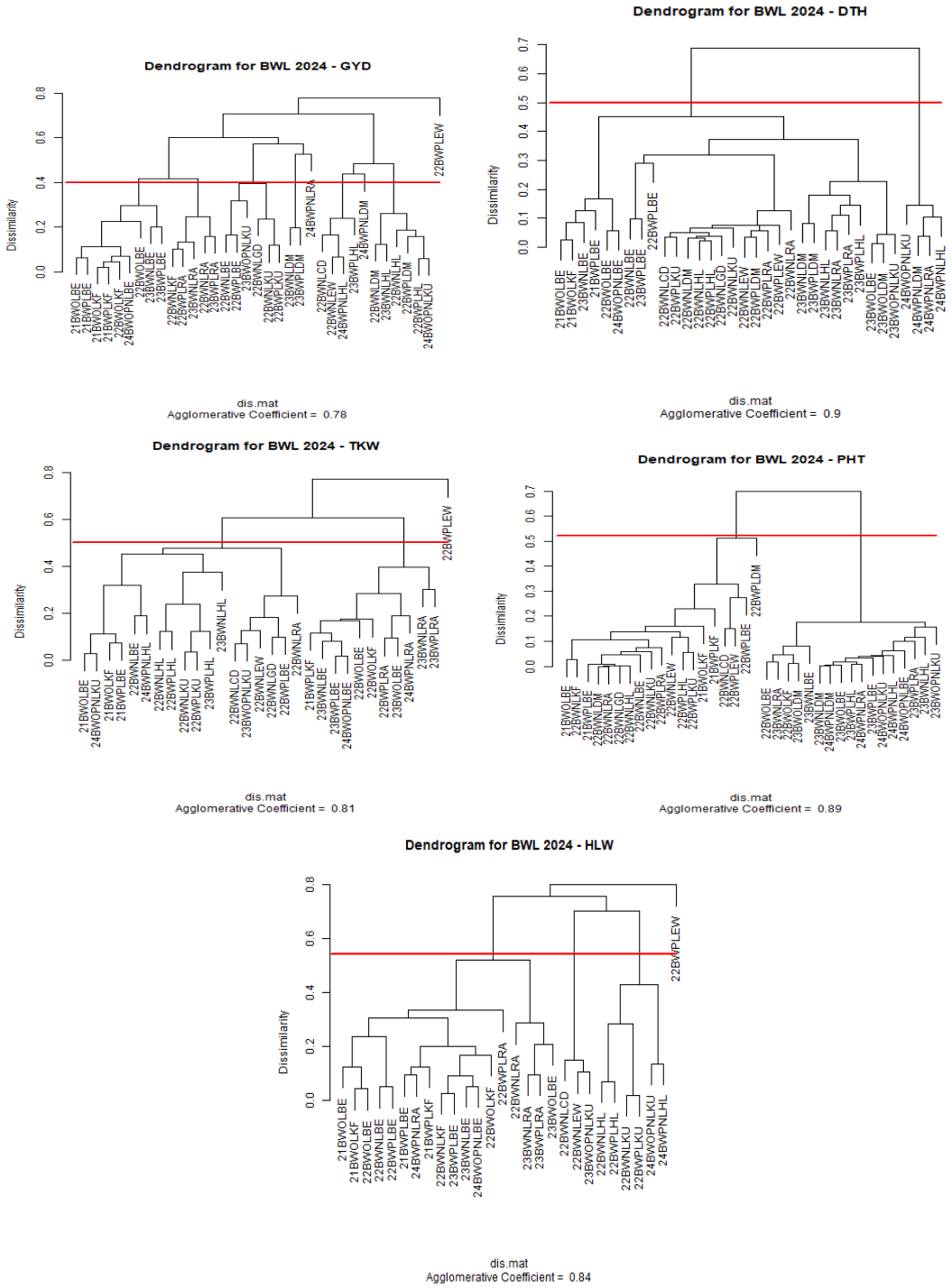



Fig 1. Dendrogram of the dissimilarity matrix from the final FA models.

In this study, heatmaps of genetic correlations were generated to visualize relationships among environments (Fig. 2) for each trait, with the color gradient indicating the strength and direction of environmental similarity. Deep red cells indicated strong positive correlations, signifying environments with similar genetic responses, while deep blue cells highlighted strong negative correlations, indicating contrasting growing conditions. As noted by Smith and Cullis (2018), these visual tools were essential for Multi-Environment Trial (MET) analysis, clarifying the correlation structures that inform regional breeding decisions. Hence, based on the results of this study, the genetic correlation analysis for GYLD revealed a complex landscape of environmental interactions across the network of high-altitude bread wheat trial sites. Thus, distinct clusters of high positive correlations were identified,

particularly among sites such as 21BWOLBE, 21BWPLBE, and 21BWOLKF, where correlation coefficients reached near-unity. These clusters defined specific "mega-environments" in which genotype-by-environment interaction (GEI) is minimized, showing that such alignment enables the consolidation of breeding resources by selecting representative sites to predict performance across the group. The consistency in these highland clusters suggests that physiological mechanisms, such as nutrient uptake efficiency and frost resilience, remain stable (Bornhofen *et al.*, 2021). Conversely, low-to-moderate correlations between distant clusters—notably between 23BWNLRA and the EBWOLBE group—indicated significant environment-specific genetic expression. These findings implied that different genetic makeup enhanced yield under varying local stressors, such as moisture fluctuations or soil acidity, which are common in Ethiopian highland vertisols (Zemede *et al.*, 2024). For the national program, these low-correlation zones necessitate continued multi-environment trials (METs) to capture crossover interactions. Success in stable environments did not necessarily translate to these variable locations, reinforcing the need for site-specific selection (Tolessa *et al.*, 2024; Tadesse *et al.*, 2025).

Moreover, genetic correlation for DTH indicated high environmental uniformity across most sites, particularly for the 2024 trials. A central cluster, including 22BWNLCD, 22BWPPLKU, 22BWNLHL, and 22BWPLHL, exhibited a near-perfect positive correlation, indicating that genotype rankings for flowering time were highly stable, allowing selection at one site to effectively predict outcomes at others. Such high correlations are typical of phenological traits, which generally exhibit higher heritability and lower GEI than polygenic traits such as yield (Kabir *et al.*, 2024). However, peripheral sites such as 24BWPNLKU and 21BWOLBE showed significantly lower correlations, indicating greater environmental sensitivity. These likely represented unique agro-climatic zones where specific cues, such as photoperiod or temperature variations at different elevations, caused divergent genetic pathways (Masawi *et al.*, 2025). Generally, the genetic control of flowering time remained remarkably consistent across the highland environments tested in Ethiopia, despite specific outliers that responded differently to local conditions. For PHT, the genetic correlation matrix indicated significant clustering and varying degrees of stability. High positive correlations, approaching unity, were observed in a cluster comprising 21BWOLBE, 22BWNLRA, 22BWPLRA, and 22BWPLHU, facilitating predictable selection outcomes (Begna and Begna, 2025). Conversely, lower correlation values (0.0–0.5) were observed at more recent sites such as 24BWPNLDM and 23BWOPNLKU. This divergence highlighted substantial GEI, suggesting that shifting climatic factors or management practices were introducing new sources of variation for plant height. As proposed by Lee *et al.* (2025), advanced spatial factor-analytic approaches are essential for accurately partitioning these shifting genetic effects in modern breeding cycles, especially since plant architecture directly influences lodging resistance.

Regarding TKW, most sites exhibited a complex landscape of interactions, with most site-to-site comparisons showing robust positive correlations, consistent with Cooper *et al.* (2021), who noted that yield components such as kernel weight generally exhibit lower GEI than total grain yield. However, site 22BWPLBW was a significant outlier, displaying near-zero correlations. This suggested unique stressors, likely terminal frost or other stresses, which altered the typical grain-filling process in that specific highland zone (Crespo-Herrera *et al.*, 2021). Moreover, the correlation matrix for hectoliter weight (HLW) revealed high genetic similarity across most environments, with strong correlations (>0.70) in the primary cluster. Nevertheless, a second cluster exhibited significant crossover GEI, particularly at 22BWNLCD and 22BWNLHL, with near-zero or negative correlations relative to the primary cluster, indicating significantly altered genotype rankings. These interactions necessitate partitioning the bread wheat breeding program into target populations of environments (TPEs) to maximize local yield potential and ensure regional food security (Mondal *et al.*, 2024). Generally, genetic correlation analysis revealed that while heading date and kernel weight remained stable across environments, grain yield and plant height exhibited site-specific variability. Hectoliter weight was generally consistent but varied across locations (Worede *et al.*, 2025). Therefore, these findings necessitated the use of Target Populations of Environments (TPEs) to tailor breeding strategies effectively across highland.

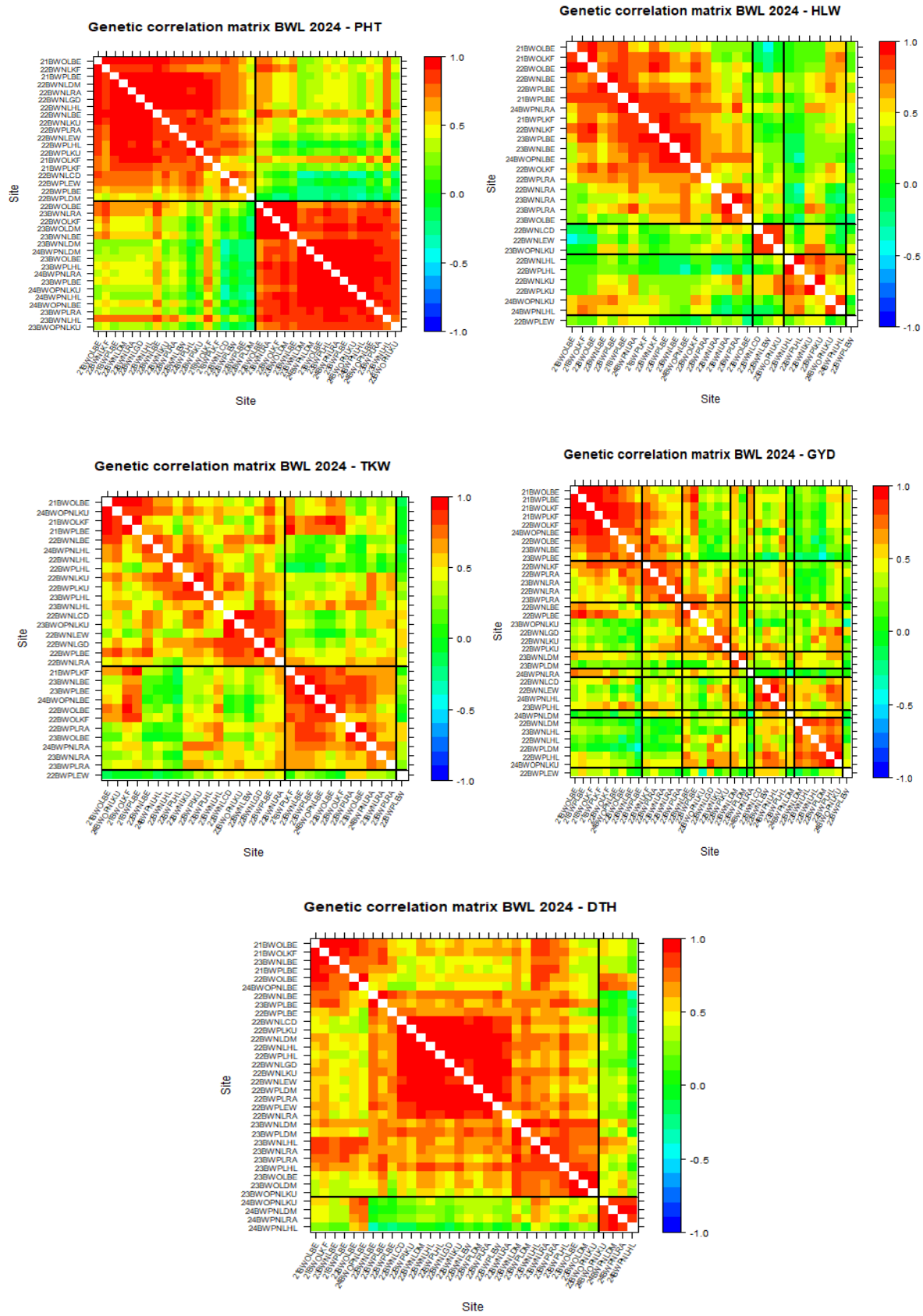



Fig 2. Heat map representation of the genetic correlation matrix from the final FA models.

***Factor analysis***

Factor analytic (FA) models were employed to analyze G×E interactions while preserving spatial variability from individual trials. Model adequacy could be assessed by the proportion of G×E variance explained by factor components, both within individual trials and across all trials (Smith *et al.*, 2018). Thus, applying an eight-factor analytic (FA_8) model to the multi-environment trial (MET) data yielded a granular decomposition of genetic variance, as summarized in Table 4. Hence, in this study, the FA models effectively estimated and predicted G×E effects and quantified G×E variance. Similar results have been reported for common bean (Argaw *et al.*, 2024), finger millet (Tesfaye *et al.*, 2023), and durum wheat (Tadese *et al.*, 2021), confirming the efficiency of FA models in MET genetic analyses. The model revealed unique expressive power, with the cumulative explained variance across the eight latent factors typically exceeding 99.9%. This indicated that the preferred FA framework was sufficient to capture the vast majority of the complex covariance structure within the genotype-by-environment interaction (Smith *et al.*, 2015). Hence, the results identified a distinct group of environments in which the first underlying factor (FA_1) was the dominant driver of genetic variation. In the 2021 and 2022 trials, sites such as 21BWOLKF (89.57%), 21BWPLKF (91.98%), and 22BWNLKF (86.37%) exhibited high FA_1 loadings, suggesting a strong genetic correlation and minimal rank change among genotypes at these locations (Beeck *et al.*, 2010). Moreover, such a trend continued into the 2024 season with 24BWOPNLBE (74.09%), indicating that these environments constituted the core of the Target Population of Environments (TPE), where selection for broad adaptation and yield stability is most effective (Cullis *et al.*, 2010).

In contrast, a significant subset of environments displayed more complex variance structures, where secondary factors (FA_2 through FA_8) were hidden or matched the primary factor. For the 2022 trials, a major shift toward Factor 2 was observed in 22BWNLHL (63.54%), 22BWNLKU (63.60%), and 22BWPLDM (62.85%) trials, showing that these high F2 loadings signify a distinct environmental stimulus—potentially related to seasonal rainfall patterns or soil characteristics—that differentiated the trials from the FA_1-dominant group (Gogel *et al.*, 2018). Similarly, 22BWPLEW was defined exclusively by FA_5 (44.00%), illustrating the model's ability to isolate niche-specific genetic responses. The 2023 and 2024 data further highlighted this environmental divergence. In site 23BWPLDM, FA_ 6 became the primary source of variation (63.77%), while 23BWOPNLKU was heavily influenced by FA_4 (37.87%). In the 2024 trials, 24BWPNLRA and 24BWPNLHL were primarily driven by FA_ 4, accounting for 39.17% and 35.02% of the variance, respectively. These findings suggested that higher-order factors are not merely noise but represent specific physiological constraints or environmental categories that require targeted selection strategies to maximize genetic gain (Piepho *et al.*, 2012). A notable finding was the discrepancy in total explained variance for site 22BWNLRA, which reached only 85.67%. This indicated a substantial proportion of "specific" or residual genetic variance (approximately 14.33%) that remains independent of the common factors shared by the rest of the testing network (Kelly *et al.*, 2007). Such environments represent unique microclimates where genotype performance may be entirely decoupled from the broader TPE. Ultimately, the distribution of loadings across the eight factors revealed a highly segmented environmental landscape. By quantifying the exact contribution of each latent factor to the total genetic variance at every site, the FA model provided a statistically rigorous foundation for identifying genotypes with either robust stability across the FA_1 dominant sites or specialized adaptation to the niches defined by factors FA_2 through FA_8 (Smith *et al.*, 2019).

Table 4. Results from fitting the factor analytic model.

| Site | FA_1 | FA _2 | FA_ 3 | FA _4 | FA _5 | FA_6 | FA_7 | FA _8 | Total |
|---|---|---|---|---|---|---|---|---|---|
| 21BWOLBE | 71.86 | 1.15 | 19.36 | 1.92 | 2.34 | 0.27 | 0.41 | 2.68 | 99.99 |
| 21BWOLKF | 89.57 | 6.00 | 3.80 | 0.00 | 0.00 | 0.00 | 0.38 | 0.24 | 99.99 |
| 21BWPLBE | 80.33 | 0.02 | 7.79 | 0.33 | 8.57 | 2.59 | 0.18 | 0.18 | 99.99 |
| 21BWPLKF | 91.98 | 4.10 | 1.81 | 0.80 | 0.58 | 0.16 | 0.55 | 0.03 | 100.01 |
| 22BWNLBE | 45.55 | 25.04 | 3.28 | 6.16 | 0.00 | 16.85 | 0.99 | 2.13 | 100.00 |
| 22BWNLCD | 24.04 | 3.31 | 1.25 | 25.85 | 4.37 | 0.43 | 33.30 | 7.44 | 99.99 |
| 22BWNLDM | 4.89 | 45.93 | 18.69 | 4.57 | 17.82 | 0.10 | 2.67 | 5.34 | 100.01 |
| 22BWNLEW | 15.66 | 48.32 | 0.03 | 18.15 | 10.91 | 0.13 | 5.39 | 1.42 | 100.01 |
| 22BWNLGD | 21.20 | 46.01 | 0.20 | 0.29 | 5.72 | 2.18 | 23.30 | 1.11 | 100.01 |
| 22BWNLHL | 5.24 | 63.54 | 15.31 | 0.23 | 10.04 | 0.54 | 0.00 | 5.09 | 99.99 |
| 22BWNLKF | 86.37 | 0.01 | 7.22 | 0.74 | 4.67 | 0.03 | 0.92 | 0.05 | 100.01 |
| 22BWNLKU | 16.06 | 63.60 | 0.71 | 12.39 | 0.02 | 1.61 | 0.06 | 5.55 | 100.00 |
| 22BWNLRA | 45.92 | 7.52 | 23.96 | 0.39 | 1.84 | 1.91 | 4.05 | 0.08 | 85.67 |
| 22BWOLBE | 68.04 | 9.68 | 1.10 | 8.21 | 3.68 | 2.09 | 0.26 | 6.94 | 100.00 |
| 22BWOLKF | 83.13 | 6.10 | 4.04 | 1.62 | 0.34 | 1.45 | 2.02 | 1.30 | 100.00 |
| 22BWPLBE | 74.10 | 4.07 | 0.71 | 6.63 | 5.34 | 5.30 | 3.85 | 0.00 | 100.00 |
| 22BWPLDM | 1.21 | 62.85 | 8.60 | 15.81 | 0.82 | 3.43 | 7.28 | 0.02 | 100.02 |
| 22BWPLEW | 11.99 | 0.01 | 2.30 | 25.45 | 44.00 | 0.42 | 7.06 | 8.77 | 100.00 |
| 22BWPLHL | 23.70 | 52.68 | 13.78 | 6.29 | 0.09 | 1.78 | 1.24 | 0.44 | 100.00 |
| 22BWPLKU | 29.47 | 47.61 | 4.21 | 2.60 | 8.70 | 6.44 | 0.91 | 0.06 | 100.00 |
| 22BWPLRA | 67.40 | 0.00 | 24.51 | 4.31 | 1.43 | 0.40 | 1.30 | 0.63 | 99.98 |
| 23BWNLBE | 70.56 | 6.82 | 2.03 | 0.22 | 3.93 | 0.21 | 14.83 | 1.40 | 100.00 |
| 23BWNLDM | 41.21 | 18.09 | 5.15 | 0.03 | 0.11 | 26.26 | 0.80 | 8.34 | 99.99 |
| 23BWNLRA | 58.92 | 2.06 | 29.68 | 0.64 | 0.54 | 5.92 | 0.46 | 1.78 | 100.00 |
| 23BWOPNLKU | 13.42 | 32.41 | 2.84 | 37.87 | 1.23 | 2.93 | 0.20 | 9.11 | 100.01 |
| 23BWPLBE | 49.42 | 27.96 | 3.96 | 2.46 | 12.96 | 0.30 | 1.91 | 1.03 | 100.00 |
| 23BWPLDM | 7.65 | 10.87 | 5.82 | 1.76 | 9.53 | 63.77 | 0.54 | 0.06 | 100.00 |
| 23BWPLHL | 45.99 | 2.99 | 0.46 | 28.06 | 0.28 | 12.81 | 7.72 | 1.69 | 100.00 |
| 23BWPLRA | 49.34 | 13.98 | 17.73 | 17.00 | 0.04 | 0.96 | 0.75 | 0.20 | 100.00 |
| 24BWOPNLBE | 74.09 | 11.15 | 9.36 | 3.19 | 2.05 | 0.06 | 0.07 | 0.03 | 100.00 |
| 24BWOPNLKU | 35.99 | 43.47 | 5.85 | 10.97 | 0.32 | 0.14 | 2.48 | 0.77 | 99.99 |
| 24BWPNLDM | 9.21 | 27.61 | 16.15 | 15.91 | 3.77 | 8.82 | 9.05 | 9.48 | 100.00 |
| 24BWPNLHL | 21.78 | 22.97 | 0.00 | 35.02 | 3.76 | 2.78 | 13.34 | 0.37 | 100.02 |
| 24BWPNLRA | 32.38 | 0.04 | 12.65 | 39.17 | 5.06 | 10.59 | 0.11 | 0.00 | 100.00 |

***Disease reaction and mean performance of advanced genotypes***

The evaluation of advanced bread wheat genotypes and two commercial checks revealed significant genetic variability in resistance to yellow rust (Yr) and stem rust (Sr), as well as in mean trait performance across two testing environments (Table 5). At the Meraro site, the lowest yellow rust scores were recorded for genotypes EBW170051 (1.47) and EBW170058 (1.54), both of which performed comparably to the resistant commercial check, Kulumsa (1.55). These high levels of resistance were notably associated with longer phenological cycles; for example, EBW170058 recorded the maximum of 77.49 days to heading (DTH), suggesting a possible correlation between extended vegetative growth and rust resilience in this specific germplasm. Conversely, genotypes EBW233267 and EBW233059 displayed high susceptibility to yellow rust with scores of 7.06 and 6.81, respectively. Notably, the earliest maturing genotype, EBW233267 (70.19 DTH), exhibited the highest susceptibility, indicating that early heading did not serve as an effective escape mechanism against yellow rust in this environment. Regarding stem rust (Sr) at the Debrezeit site, reactions were more uniform among the genotypes, though distinct levels of terminal resistance were observed. Thus, genotype EBW222276 demonstrated the most robust resistance at this location with a score of 5.01. In contrast, the majority of the EBW1700 series reached a susceptibility peak of 6.80 at Debrezeit, suggesting a potential breakdown of resistance under the high inoculum pressure characteristic of that specific site. These results align with findings by Figueroa *et al.* (2018) and Singh *et al.* (2020), which emphasized that multi-location screening is essential for identifying genotypes with broad-spectrum and durable resistance against evolving rust races.

On the other hand, mean grain yield (GYLD) across the genotypes was highly variable, ranging from 3.02 t ha$^{-1}$ to 5.31 t ha$^{-1}$. The advanced genotypes EBW170049 (5.31 t ha$^{-1}$) and EBW170074 (5.17 t ha$^{-1}$) achieved the highest mean yield, followed closely by EBW222923 (5.06 t ha$^{-1}$) and EBW170051 (5.03 t ha$^{-1}$). The superior performance of

EBW170049 was complemented by strong grain quality parameters, including a Hectoliter Weight (HLW) of 70.37 kg $hl^{-1}$ and a Thousand Kernel Weight (TKW) of 38.46 g, suggesting a stable and efficient grain-filling period. On the other hand, the check Danda'a and the genotype EBW233267 recorded the lowest yields of 3.02 t $ha^{-1}$ and 3.10 t $ha^{-1}$, respectively. This reduction in yield appeared to correlate directly with higher disease pressure and lower TKW. Additionally, genotype EBW170074 was particularly notable for producing the highest TKW in the study (41.25 g), outperforming both commercial checks and all other entries. Such variations in yield components are typical in advanced wheat germplasm, where high kernel weight often compensates for fewer tillers or shorter grain-filling durations (Gazzola *et al.*, 2021).

Furthermore, phenological development and plant architecture also showed significant differences ($P<0.05$) among the tested genotypes. Days to heading (DTH) ranged from a minimum of 70.19 days in EBW233267 to a maximum of 77.49 days in EBW170058. While early heading is often viewed as an escape mechanism for terminal stresses, in this study, it was associated with lower yield potential and higher disease susceptibility. In terms of plant height (PHT), the check Danda'a and genotype EBW160066 reached the maximum height of 101.42 cm, while the shortest stature was observed in EBW222919 at 87.82 cm. Genotype EBW222276 also maintained a semi-dwarf stature of 88.68 cm while providing robust resistance to stem rust. The integration of reduced plant height in these genotypes suggests improved lodging resistance, which remains a key objective in modern wheat breeding for high-productivity systems (Würschum *et al.*, 2018). Ultimately, the EBW1700 series—specifically EBW170049 and EBW170074—performed as the most promising candidates, successfully combining high grain yield (up to 5.31 t $ha^{-1}$) and superior kernel weight (41.25 g) with competitive resistance against yellow and stem rust profiles and stable phenological development. Moreover, EBW222276 was also identified as a critical genetic resource for its robust terminal stem rust resistance and desirable semi-dwarf architecture. The integration of high yield potential, superior kernel weight, and broad-spectrum rust resistance makes these advanced genotypes the best candidates for variety development. Consequently, they are the most promising selections for formal release or as parental lines in future breeding programs designed to boost productivity in rust-prone highland areas of Ethiopia.

Table 5. Disease reaction and mean traits of advanced genotypes with two checks.

| Genotypes | Yellow Rust (Yr) | | Stem Rust (Sr) | Mean of traits | | | | |
|---|---|---|---|---|---|---|---|---|
| | Meraro | Bekoji | Debrezeit | GYLD | DTH | HLW | PHT | TKW |
| EBW202276 | 3.49 | 4.47 | 6.70 | 4.91 | 71.9 | 70.70 | 88.96 | 35.48 |
| EBW212274 | 2.79 | 3.98 | 5.90 | 4.34 | 72.98 | 66.68 | 90.33 | 37.94 |
| EBW160066 | 1.92 | 3.42 | 5.18 | 4.32 | 70.81 | 69.83 | 101.4 | 38.86 |
| EBW222276 | 3.13 | 4.30 | 5.01 | 4.58 | 73.95 | 72.04 | 88.68 | 39.19 |
| EBW233267 | 7.06 | 7.01 | 5.24 | 3.10 | 70.19 | 64.17 | 90.64 | 31.87 |
| EBW170049 | 1.68 | 3.27 | 6.80 | 5.31 | 76.63 | 70.37 | 98.24 | 38.46 |
| EBW170051 | 1.47 | 3.15 | 6.80 | 5.03 | 77.43 | 70.64 | 94.71 | 37.94 |
| EBW170052 | 1.82 | 3.35 | 6.80 | 4.63 | 74.11 | 70.71 | 94.87 | 38.68 |
| EBW170057 | 2.24 | 3.60 | 6.80 | 4.55 | 72.66 | 70.46 | 94.59 | 37.95 |
| EBW170058 | 1.54 | 3.16 | 6.80 | 4.91 | 77.49 | 71.00 | 97.41 | 39.95 |
| EBW170074 | 2.60 | 3.89 | 6.10 | 5.17 | 71.04 | 69.96 | 95.92 | 41.25 |
| EBW222919 | 3.04 | 4.21 | 5.57 | 4.11 | 71.71 | 67.30 | 87.82 | 40.83 |
| EBW222923 | 2.15 | 3.53 | 5.94 | 5.06 | 73.9 | 69.75 | 87.87 | 38.15 |
| EBW233059 | 6.81 | 6.85 | 6.08 | 3.63 | 72.38 | 64.79 | 88.06 | 35.64 |
| EBW232809 | 2.92 | 4.06 | 5.48 | 4.18 | 72.52 | 70.06 | 92.12 | 38.05 |
| EBW232499 | 1.75 | 3.32 | 5.48 | 4.01 | 73.33 | 68.65 | 89.82 | 36.83 |
| Danda'a | 4.57 | 5.28 | 6.16 | 3.02 | 76.91 | 60.34 | 101.42 | 32.03 |
| Kulumsa | 1.85 | 3.84 | 6.93 | 4.47 | 73.12 | 71.02 | 94.46 | 40.27 |

## Conclusion

The evaluation of bread wheat trials across the Ethiopian highlands from 2021 to 2024 established that productivity was fundamentally governed by complex Genotype by Environment (G×E) interactions, with grain yields fluctuating significantly between 1.54 and 7.39 t $ha^{-1}$ across environmental sites. Using a Factor Analytic Mixed Model (FAMM), the study partitioned 99.9% of the genetic variance and identified 65% of elite genotypes that consistently surpassed the 4.5 t $ha^{-1}$ threshold across diverse agro-ecologies such as 24BWOPNLBE and 22BWNLHL. The top performing genotypes EBW170049 (5.31 t $ha^{-1}$) and EBW170074 (5.17 t $ha^{-1}$), followed closely by EBW222923 (5.06 t $ha^{-1}$) and EBW170051 (5.03 t $ha^{-1}$), achieved stability through a high-yield, early-maturity ideotype, characterized by a semi-dwarf architecture and a precise day to heading frame, which served as a critical stress-escape strategy. Hierarchical clustering and Factor_1 loadings exceeding 85% at sites such as Bekoji and Kulumsa confirmed the Arsi highlands as the core Target Population of Environments (TPE), where high broad-sense heritability of phenological traits enabled breeders to maintain a stable maturity window despite varying altitudes and seasonal rainfall. Hence, environmental clustering successfully partitioned the test sites into distinct mega-environments based on their discriminatory power and representativeness**,** highlighting that while most Arsi highland locations were highly correlated, specific seasons exhibited outlier behaviors due to erratic rainfall distributions that disrupted traditional genetic rankings. The identification of ecological outliers such as Enawari (22BWPLEW) and Arsi-Robe (22BWNLRA) highlighted unique physiological constraints that were often obscured by regional averages.

Furthermore, correlation analysis and disease screening revealed that while yield was positively associated with quality parameters such as Hectoliter Weight (HLW > 78 kg $hL^{-1}$) and Thousand Kernel Weight (TKW), it showed a strong negative correlation with rust severity, particularly in hotspots like Meraro. The EBW1700 series genotypes, notably EBW170049 and EBW170074, demonstrated significant genetic progress by combining high productivity with broad-spectrum rust resistance, achieving yields up to 5.31 t $ha^{-1}$ and a TKW of 41.25 g, representing a 9–14% advantage over standard checks. Conversely, early-maturing genotypes such as EBW233267 failed to escape virulent rust races in high-pressure areas, proving that phenological escape must be integrated with robust genetic resistance to prevent kernel shriveling and yield loss. Ultimately, while EBW222276 offered valuable specific stem rust resistance, the EBW1700 series and related elite genotypes were designated the highest priority for variety advancement due to their superior stability, milling quality traits, and their ability to maintain high harvest indices under the combined pressures of biotic stress and shifting climatic patterns across the moisture-variable and disease-prone environments of wheat belt highland areas of Ethiopia. In summary, the study successfully applied FAMM-based MET analysis to identify top-performing genotypes, thereby offering breeding programs a proven methodology to accelerate genetic gains and secure climate-resilient wheat production under highland agroecologies of Ethiopia.

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# Determinants of the use of Uganda's e-diary application in agricultural extension monitoring and supervision

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**A B S T R A C T**

Information and Communication Technologies (ICTs) are increasingly recognized for improving service delivery, yet their role in monitoring and supervising agricultural extension services remains underexplored. This study examined the determinants of the use of the E-dairy ICT application, introduced in Uganda in 2019 to strengthen monitoring and supervision within the public agricultural extension system. Guided by the Unified Theory of Acceptance and Use of Technology (UTAUT), the study employed an exploratory sequential mixed-methods design involving 246 randomly selected extension workers. Structural Equation Modelling (SEM) in R and thematic content analysis were used to analyze quantitative and qualitative data, respectively. Results revealed low overall usage (22%), particularly among frontline extension workers. Technical capacity was the strongest determinant of use (β = 0.562), followed by attitudes (β = 0.309) and motivation (β = 0.242), while social influence negatively affected use (β = −0.178). The findings suggest the need for continuous technical training, decentralized support systems, and institutional facilitation to enhance ICT uptake. The study concludes that effective digital extension systems require not only technological investment but also strengthened human and organizational capacity to support sustainable agricultural service delivery.

**Keywords:** E-Diary Application, Use, Agriculture Extension Service, Monitoring, Supervision

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## Introduction

Advancements in Information and Communication Technologies (ICTs) have accelerated government efforts to digitize service delivery, monitoring, and supervision across sectors globally. Governments in both developed and developing countries increasingly invest in digital infrastructures and platforms to improve efficiency, accountability, transparency, and coordination in public service systems (Sharmin *et al.*, 2017; Nassar *et al.*, 2019; Makini *et al.*, 2020; Yang and Ou, 2023; Karubanga *et al.*, 2024; Tandon and Kandathil, 2025). Globally, digital monitoring and reporting systems are increasingly being adopted in sectors such as agriculture, health, education, and social protection to facilitate real-time information sharing, evidence-based decision-making, and institutional accountability. In developed economies, digital platforms have improved coordination, data management, and performance monitoring within public institutions. Similarly, in Sub-Saharan Africa, governments and development partners have promoted ICT-enabled systems to strengthen agricultural extension services, improve supervision, reduce operational costs, and support geographically dispersed extension structures (Aker and Mbiti, 2010; Trendov *et al.*, 2019). Countries such as Kenya, Rwanda, Ghana, and Ethiopia have implemented mobile-based agricultural platforms to support farmer advisory

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services, extension reporting, supervision, and knowledge exchange. However, despite increasing investments in digital extension systems, evidence from Sub-Saharan Africa indicates that many ICT interventions continue to face challenges, including limited technical capacity, infrastructural constraints, weak institutional support, digital inequalities, and low utilization among frontline extension workers (Baumüller, 2018; Bonina *et al.*, 2021). These experiences suggest that the effectiveness of digital monitoring systems depends not only on technological availability but also on broader socio-technical and organizational conditions that shape their practical use and sustainability.

In agriculture, ICT-based platforms are increasingly promoted as tools to strengthen extension systems by improving information management, coordination, accountability, and monitoring of service delivery. Uganda has similarly embraced e-governance and digital transformation in sectors such as agriculture, education, and health (Gillwald, 2019). Within this agenda, the Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) introduced the E-diary application in 2019 to support monitoring and supervision of agricultural extension services (Namyenya *et al.*, 2022). The application is a mobile and web-based reporting platform designed to capture extension activities and facilitate information exchange across local and national government structures.

Despite growing optimism surrounding digital technologies in development, critical ICT4D scholarship cautions against assuming that technology adoption automatically translates into development outcomes. Existing studies argue that digital technologies are socially embedded and shaped by institutional, political, and infrastructural inequalities that influence how technologies are adopted and used (Roztocki *et al.*, 2019). Recent debates further warn that digital policies and platforms may reproduce exclusion, deepen inequalities, or fail to achieve intended outcomes when contextual realities, governance systems, and institutional capacities are overlooked (Zamani and Vannini, 2025; Kleine and Braido, 2024). Consequently, the effectiveness of ICT-enabled systems cannot be understood solely through assumptions of technological efficiency or innovation diffusion. Rather, there is a need to critically examine how digital tools are used in institutional settings, the constraints that affect their use, and the socio-technical conditions that shape adoption and continued engagement.

## Materials and Methods

This study was guided by the Unified Theory of Acceptance and Use of Technology (UTAUT), which explains technology use through four major constructs: performance expectancy, effort expectancy, social influence, and facilitating conditions (Arenas Gaitán *et al.*, 2015; Marikyan and Papagiannidis, 2021). UTAUT was adopted to examine the continued and practical use of the E-diary application within Uganda's public agricultural extension system. In this study, performance expectancy was operationalized as users' motivation to use the application, effort expectancy as individual technical capacity, while social influence and facilitating conditions were conceptualized as institutional and interpersonal factors affecting application use.

The study was conducted in six purposively selected districts in Uganda where the E-diary application had been operationalized by July 2024. These districts included Kasese, Rubanda, Kibaale, Kyenjojo, Oyam, and Serere. District selection was based on records obtained from the Ministry of Agriculture, Animal Industry and Fisheries (MAAIF), with a particular focus on districts with relatively high numbers of extension workers. Selecting districts with larger extension staff establishments provided broader experiences and insights regarding the implementation and practical use of the application across different administrative and agricultural contexts. The study targeted actors involved in Uganda's public agricultural extension system at national, district, and sub-county levels. An exploratory sequential mixed-methods research design was adopted to provide both contextual depth and empirical explanation of the use of the E-diary application. Participants' experiences, perceptions, and institutional realities were explored first, followed by quantifying the observed patterns using survey data. In the qualitative phase, data were collected to understand how the application was used. Insights generated from this phase informed the refinement of the quantitative survey instrument and the operationalization of key study variables.

Qualitative data were collected through six Focus Group Discussions (FGDs) involving 60 extension workers and ten Key Informant Interviews (KIIs). One FGD was conducted in each district, targeting frontline extension

workers, who were the primary users of the E-diary application. The KIIs included six District Production and Marketing Officers and four MAAIF officials responsible for ICT management, monitoring and evaluation, extension communication, and supervision of the E-diary system.

Quantitative data were collected from 246 extension workers selected from a target population of 367 staff across the six districts. The sample size was determined using Cochran's formula for survey studies, with a 95% confidence level and a 5% margin of error (Uakarn *et al.*, 2021). Proportionate stratified sampling was used to allocate respondents across districts, while simple random sampling was applied to select individual participants.

Data were collected using interview guides for qualitative inquiry and a semi-structured questionnaire for the survey. Variables assessed included attitudes, motivation, social influence, facilitating conditions, and technical capacity in terms of ICT knowledge and skills. Qualitative data were analyzed using thematic content analysis, while quantitative data were analyzed in R using descriptive statistics and Structural Equation Modelling (SEM) to examine determinants influencing the use of the E-diary application.

## Results and Discussion

### *Socio-demographic profile of agricultural extension staff*

Among the 246 agricultural extension staff who participated in the study, 72.8% were male. This reflects broader structural patterns in agricultural extension systems in many developing countries, where field-based roles have historically been dominated by men due to mobility requirements and established occupational norms. In terms of educational attainment, just over half of the respondents (50.8%) held bachelor's degrees, while 44.3% possessed diplomas. A small proportion had master's degrees (3.3%) and other post-secondary qualifications (1.6%). This indicates a generally well-qualified workforce, which is important for the effective adoption and use of digital tools such as the E-diary system. Staff with higher levels of education are more likely to interpret digital data, generate reports, and integrate ICT-based solutions into routine extension work, thereby improving service delivery. Regarding age distribution, most respondents (69.3%) were aged 40 years and below, with a mean age of 38.8 years. This relatively young workforce is favorable for ICT adoption, as younger professionals tend to be more adaptable to technological innovations, consistent with the Unified Theory of Acceptance and Use of Technology (UTAUT) and Diffusion of Innovations theory. All participants were on permanent employment terms. In addition, 53.3% had 6–10 years of experience, 35% had 1–5 years, and 11.8% had over 10 years. This demonstrates a moderately experienced workforce familiar with extension service delivery challenges and supportive of the E-diary system's relevance across agricultural sectors.

### *Use of the e-diary application among extension workers*

The findings indicate that actual usage remains very low at 22%, with some districts reporting no active users. Notably, supervisors do not use the system to monitor or support field staff, suggesting weak institutional enforcement. This low adoption reflects not only limited technical capacity among users but also inadequate supervisory engagement and follow-up, which are essential for sustaining ICT use in organizational settings.

FGD findings indicated a general decline in sustained use of the E-diary application among extension workers and their supervisors after initial training. In Rubanda District, an FGD participant reported, *"I stopped using it in training,"* suggesting early discontinuation of use even during the capacity-building phase. Similarly, a key informant observed,

The number of extension workers who are still using the system is very few compared to the number we started with, and I don't know, some are complaining that when the phone gets lost or blacks out, they cannot get back on the system.

This highlights both usage attrition and technical challenges related to device dependency and system recovery. The decline in continued use reflects reduced engagement after training, with many extension workers discontinuing use over time. This was largely driven by reliance on individual mobile devices, where loss, damage, or system failure resulted in loss of access to the application. Limited recovery options and weak reinstallation support further worsened the situation. As a result, data entry and reporting were disrupted, discouraging sustained adoption of the E-diary system in routine extension work.

Participants further noted that transfers to new administrative locations limited continued use, as the application does not automatically adjust user profiles or reporting structures to reflect new sub-counties, thereby constraining data capture in new work environments. This rigidity was associated with reduced motivation and increased dropout from system use. In addition, inadequate technical training emerged as a major barrier. One participant stated, *"the biggest challenge we always face with these applications is that the trainers come when they do not have enough time to train,"* implying insufficient training duration and depth, which undermines user competence and confidence.

In Kyenjojo District in particular, respondents also indicated that although the application was launched and issues were raised, the lack of feedback and system responsiveness further discouraged continued use. Overall, these challenges collectively contributed to reduced adoption and sustained utilization of the E-diary application. Similar patterns of underutilization have been reported in other digital agriculture systems due to limited support (Pearce *et al.*, 2014; Drewry *et al.*, 2022; Thapa *et al.*, 2026).

***Determinants of e-diary application use***

Structural Equation Modelling (SEM) was used to determine the extent to which the selected predictor variables influenced the use of the E-diary application, as presented in Table 1 below.

Table 1. SEM regression coefficients predicting e-diary application use.

| Predictor | B | SE | z | p | β |
|---|---|---|---|---|---|
| Motivation | 0.273 | 0.100 | 2.735 | .006 | 0.242 |
| Attitude | 0.366 | 0.097 | 3.780 | < .001 | 0.309 |
| Social Influence | −0.191 | 0.078 | −2.442 | .015 | −0.178 |
| Technical Capacity | 0.684 | 0.065 | 10.509 | < .001 | 0.562 |

***$R^2$ (e-diary application use) = 0.770***

The model demonstrated strong explanatory power, with an $R^2$ = 0.770 for E-Diary application use, indicating that 77% of the variance in usage was explained jointly by motivation, attitude, social influence, and technical capacity. Table 1 above presents the standardized and unstandardized regression coefficients, standard errors, z-values, and significance levels, with statistical significance set at $p < 0.05$.

Results further show that motivation had a significant positive effect on E-Diary use (β = 0.242, SE = 0.100, z = 2.735, p = 0.006), indicating that higher levels of motivation were associated with a greater likelihood of E-Diary use, controlling for other factors. Attitude also had a significant positive effect (β = 0.309, SE = 0.097, z = 3.780, $p < 0.001$) and emerged as the strongest psychosocial predictor, suggesting that favourable perceptions of the system substantially enhanced adoption. In contrast, social influence exhibited a significant negative effect (β = −0.178, SE = 0.078, z = −2.442, p = 0.015), indicating that external pressures or perceived expectations were associated with reduced likelihood of use in this context.

The null hypothesis stating that E-Diary use does not depend on psychosocial factors was therefore rejected. Similarly, the second null hypothesis was also rejected, as technical capacity showed a strong and significant positive effect on use (β = 0.562, SE = 0.065, z = 10.509, $p < 0.001$) and was the most influential predictor in the model.

Overall, these findings confirm that both psychosocial and technical factors significantly influence the use of E-Diary applications among extension workers. This means that E-Diary application use among extension workers is influenced by both psychosocial factors (such as motivation, attitude, and social influence) and technical capacity (digital skills and ability to use the system). In other words, adoption is shaped not only by how users perceive and feel about the application, but also by whether they have the required skills to use it effectively, with technical capacity playing the strongest role.

These results are further illustrated in the Structural Model Diagram (Figure 1), which visually presents the magnitude and direction of the standardized path coefficients linking each predictor to E-Diary application use. The diagram confirms that technical capacity has the strongest positive influence, followed by attitude and motivation, while social influence exerts a negative effect. Overall, the model demonstrates strong predictive validity in explaining E-Diary adoption behaviour.

***Structural model diagram***

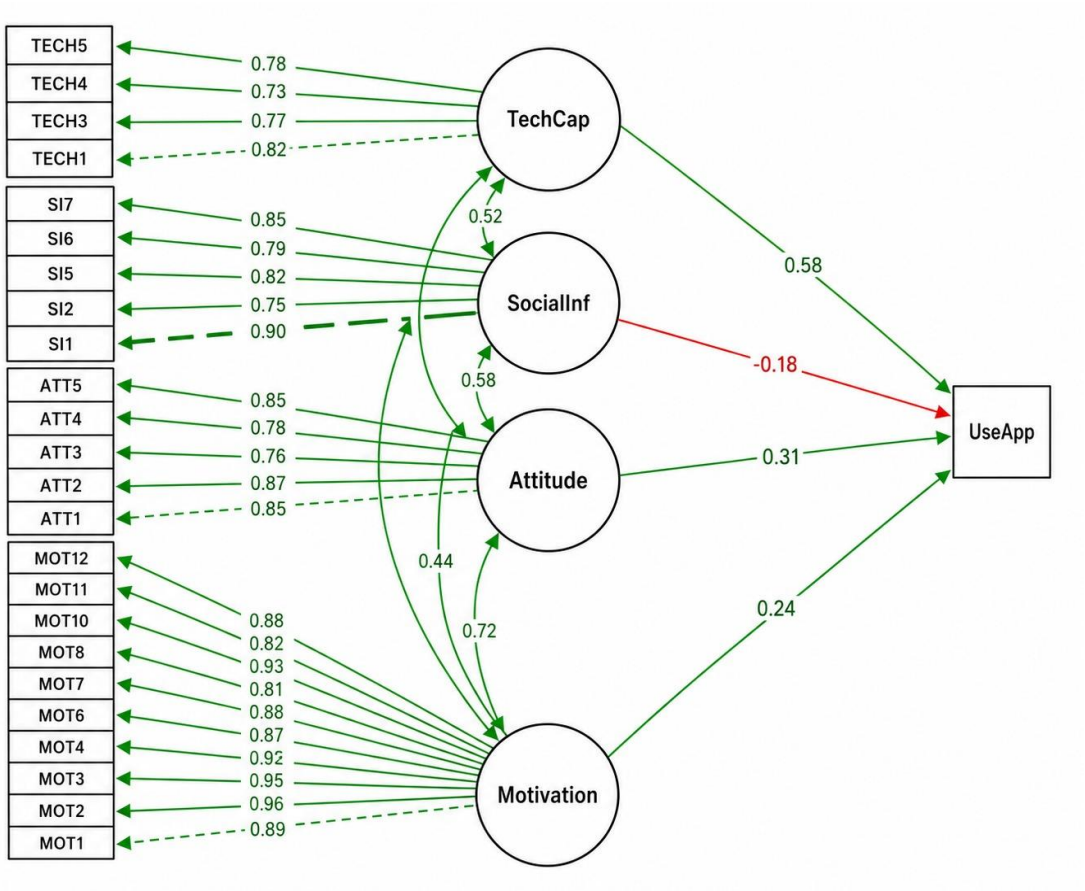



Fig. 1. Structural equation model showing standardized path coefficients for Predictors of E-diary application use.

The significant influence of technical capacity in this study aligns with Hussaini *et al.* (2021) and Chouhan *et al.* (2023), who emphasize that digital literacy is a critical determinant of ICT uptake among agricultural stakeholders. Similarly, the need for structured guidance and institutional support aligns with findings from Abedi (2024) and Khatri *et al.* (2024), who argue that targeted users require continuous technical assistance from implementing stakeholders.

The negative relationship between social influence and E-Diary use (β = −0.178) contrasts with traditional ICT adoption models, where social pressure typically enhances uptake. This finding suggests that weak supervisory engagement may have transformed social influence from a facilitator to a deterrent. This aligns with Lorenz and Buhtz (2017) and Graf-Vlachy *et al.* (2018), who note that social influence can be ineffective or counterproductive when institutional leadership is weak, but contrasts with Nassar *et al.* (2019), who found a positive effect in other contexts. Consistent with this, the results support earlier studies showing that ICT adoption is shaped by factors beyond perceived usefulness, including user skills and resource availability (Chukwuere and Ejoke, 2019; Davis *et al.*, 2021). Overall, these findings demonstrate that while technical capacity is the strongest determinant of use, institutional, infrastructural, and managerial factors collectively shape adoption outcomes. This supports ICT adoption theory by showing that even when perceived usefulness is high, structural and organizational barriers can significantly limit effective utilization (Zamani and Vannini, 2025).

## Conclusions

This study assessed the determinants of ICT use in monitoring and supervision of public agricultural extension services, using Uganda's E-Diary application as a case study. It examined the factors influencing the adoption and utilization of the system within the agricultural extension service delivery framework. Whereas digitalization of monitoring and supervision is essential for

enhancing efficiency, accountability, and service delivery by addressing the limitations of traditional approaches, including irregular field visits, delayed reporting, high operational costs, and limited coverage in remote areas, the study establishes that actual use of the application remains very low across all levels of extension service delivery, with variation across districts, indicating that ICT adoption is both limited and context-specific. This demonstrates that the availability of technology alone is insufficient to ensure uptake.

Key determinants, including limited technical capacity, weak institutional enforcement, inadequate ICT infrastructure, and insufficient training, explain the low utilization. These factors collectively shape user behaviour, leading to partial use of system functions. To improve ICT use, coordinated interventions are required. The Ministry of Agriculture, Animal Industry and Fisheries, in collaboration with relevant ministries, should develop comprehensive ICT-in-agriculture policies with clear guidelines, mandatory use frameworks, sustainable financing, and monitoring systems. Incentives for consistent reporting should also be introduced.

In conclusion, ICT use in agricultural extension monitoring is determined by interrelated technical, institutional, and capacity factors, and the E-Diary application's effectiveness depends on addressing these determinants through coordinated policy action and adequate resourcing.

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# Role of boron, potassium, and iron in improving productivity and fruit characteristics of squash (*Cucurbita pepo* L.)

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**A B S T R A C T**

Balanced mineral nutrition, especially macronutrients and micronutrients involved in plant physiological and biochemical activities, is a key factor in improving the productivity and fruit quality of squash (*Cucurbita pepo* L.). The study was conducted at the Zakho Technical Institute, Kurdistan Region, Iraq, under greenhouse conditions during the 2025–2026 growing season to examine the effects of boron (B), potassium (K), and iron (Fe) on the growth and fruit characteristics of squash. The experiment was laid out as a split-split plot, Randomized Complete Block Design (RCBD) with three replications. Two levels of iron fertigation (0 and 2 g $L^{-1}$), two levels of potassium fertilizer (0 and 2 g $L^{-1}$), and two levels of boron foliar (0 and 2 mL $L^{-1}$) were applied. The results indicated that plant fertigation with an Iron concentration of 2 g $L^{-1}$ improved the number of fruits to 8.250 fruit $plant^{-1}$. However, foliar application of potassium at a concentration of 2 g $L^{-1}$ increased the number of fruits to 8.583 fruit $plant^{-1}$, fruit length to 12.900 cm, plant height to 81.500 cm, fruit weight to 100.588 g, and fruit diameter to 3.850 cm. Furthermore, spraying Boron at a concentration of 2 mL $L^{-1}$ increased the number of fruits to 8.417 fruits $plant^{-1}$ and plant height to 80.124 cm. The study emphasized the need to properly manage nutrients in greenhouse squash production and the possibility for balanced potassium fertilization to greatly increase fruit quality and yield.

**Keywords:** Summer squash, Boron, Potassium, Iron, Greenhouse cultivation

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## Introduction

Edible summer squash (*Cucurbita pepo* L.) of the very diverse family Cucurbitaceae is grown worldwide in temperate and subtropical regions and is native to Mexico and North America (Paris, 1996). Also, due to its widespread cultivation, summer squash has been shown to be a nutritional and medicinal treasure, having a low energy density but high amounts of vitamins (ß-carotene, A, $B_2$, C, and E), amino acids, fiber, carbohydrates, phenolics, and flavonoids (Adnan *et al.,* 2017; Martínez-Valdivieso *et al.,* 2017). Its attributes highlight its significance in human nutrition and health.

The availability of essential nutrients, primarily supplied through inorganic fertilizers, is directly related to plant growth and productivity. Fertilizers contain specific proportions of micro- and macronutrients, which play a key role in achieving optimal yields in commercial farming (Rekaby *et al.,* 2024). Boron is an essential micronutrient for cucurbitaceous plants and plays roles in physiological processes including protein synthesis, cell wall integrity, glucose metabolism, sugar translocation, hormone regulation, pollen grain germination, and pollen tube development (Rasheed, 2009).

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El-Shoura (2020) reported that foliar application of boric acid significantly improved vegetative growth, yield, and fruit quality of summer squash under high-temperature stress conditions. Similarly, Abou El-Yazeid *et al.* (2007) found that application of boron via foliar spray, when combined with bio-dissolving microorganisms, improved vegetative growth, plant pigments, nutrients (N, P, K, Mg, and B), and finally resulted in a better sex ratio and early fruit production with higher yield in squash. These results confirm the importance of boron in the quantity and quality of squash production.

One macronutrient that significantly affects a variety of physiological and biochemical processes in plants is potassium (K). These include regulating water flow, energy transfer, and cation-anion balance (Hasanuzzaman *et al.,* 2018; Wang *et al.,* 2013). Additionally, potassium plays direct roles in enzymes involved in protein and carbohydrate synthesis, which are important for fruit quality (Lester *et al.,* 2010; Hasanuzzaman *et al.,* 2018). Potassium has been shown to increase the number of pistillate flowers for a variety of reasons, including its effects on hormone production, such as gibberellins. This increases the quantity of fruits and the overall yield per plant (de Souza *et al.,* 2023; Budak and Güneş, 2023; Nassar *et al.,* 2019). Potassium was reported by Nassar *et al.* (2019) and the North Carolina Cooperative Extension (2024) to synergistically enhance vegetative growth, yield, and nutritional composition of squash fruits when applied to soils, especially at higher levels. This means that the effects of potassium are overall on both fruit yield and quality. The other micronutrient of concern is iron (Fe), which is required for plant health and productivity, especially in photosynthesis and energy production in plants, as it is needed for chlorophyll formation (Bacaicoa and García-Mina, 2009). Peppermint is prone to chlorosis due to iron deficiency and is particularly affected in alkaline, calcareous soils (Haifa Group, 2026). In cucurbit species, the use of iron is key to achieving good growth and fruit quality (Gupta *et al.,* 2022). The foliar application of iron has been reported to increase growth parameters, chlorophyll content, and fruit and seed iron content in cucumbers, thereby resulting in higher seed productivity and quality (Shebl *et al.,* 2019). Shebl *et al.* (2019) reported that the application of $Fe_3O_4$ NPs as a foliar spray significantly increased the organic matter, protein, lipid, and energy contents in squash fruits. This study aims to investigate the effects of boron, potassium, and iron on the productivity and fruit characteristics of squash (*Cucurbita pepo* L.) under greenhouse cultivation in Zakho, Kurdistan, Iraq.

## Materials and Methods

The experiment was conducted during the 2025-2026 growing season in the greenhouse of the Protected Cultivation Department at Zakho Technical Institute/Dohuk Polytechnic University to evaluate the role of boron, potassium, and iron in improving productivity and fruit characteristics of squash (*Cucurbita pepo* L.). Squash seeds were sown in seedling trays with peat moss medium on 15$^{th}$ March 2026. Healthy seedlings were transplanted into the greenhouse on 8$^{th}$ April 2026. Plants were spaced 50 cm apart and 120 cm between rows. The experiment included three factors: Iron fertigation at two concentrations (0 and 2 g $L^{-1}$), potassium fertilizer at two concentrations (0 and 2 g $L^{-1}$), and boron fertilizer at two concentrations (0 and 2 mL $L^{-1}$). The treatments were arranged in a split-split plot system, Randomized Complete Block Design (RCBD) with three replications. Iron fertigation treatments were assigned to the main plots. Potassium fertilizer treatment to the subplots and boron fertilizer treatment to the sub-subplots. A Total of eight treatment combinations (2×2×2) were evaluated, resulting in 24 experimental units. Each experimental unit consisted of 10 plants. Foliar fertilizer application was initiated on 20 April 2026 and repeated twice at 7-day intervals. All recommended greenhouse management practices, including irrigation, weed control, and pest management, were uniformly applied throughout the growing period. The recorded parameters included: No. Number of fruits per plant, plant height (cm), fruit weight (g), fruit length (cm), fruit diameter (cm). The results will be analyzed statistically using Duncan's multiple range test at 0.05 (SAS, 2007).

## Results

### *Number of fruits per plant*

The results in Table 1 indicated that fertigation with Iron and spraying potassium and Boron on Squash plants at any concentration did not significantly increase the number of fruits per plant compared with the control.

However, the interaction between iron and potassium showed no significant difference. Whereas, the highest increase in number of fruits per plant reached 9.333 fruit plant$^{-1}$ for the interaction between 2 g L$^{-1}$ potassium and 2 mL L$^{-1}$ Boron, when compared with the least value, which reached to 7.833 fruit plant$^{-1}$ for the plant treat with 2 g L$^{-1}$ potassium interacted with 0 ml L$^{-1}$ Boron, In addition, the interaction between Iron and Boron also did not had any significant difference between them

The triple interaction among Iron, potassium and Boron fertilizers factors indicated that the plants which fertigation with 0 g L$^{-1}$ Iron, and spraying 2 g L$^{-1}$ potassium and 2 mL L$^{-1}$ Boron fertilizers gave the highest value of number of fruits per plant reached 10.333 fruit plant$^{-1}$, when compared with least value which reached to 7.000 fruit plant $^{-1}$ for the plant treat with 0 g L$^{-1}$ for both Iron and potassium interacted with 2 mL L$^{-1}$ Boron.

Table 1. Effect of boron, potassium, iron, and their interaction on the number of fruits per squash plant.

| Iron g L $^{-1}$ | Potassium g L$^{-1}$ | Boron mL L$^{-1}$ | | Iron * potassium | Iron |
|---|---|---|---|---|---|
| | | 0 | 2 | | |
| 0 | 0 | 8.000b | 7.000b | 7.500 a | 8.167 a |
| | 2 | 7.333b | 10.333a | 8.833 a | |
| 2 | 0 | 8.333ab | 8.000b | 8.167a | 8.250 a |
| | 2 | 8.333ab | 8.333ab | 8.333a | |
| Iron * Boron | 0 | 7.667a | 8.667a | potassium | |
| | 2 | 8.333a | 8.167a | | |
| potassium * Boron | 0 | 8.167ab | 7.500a | 7.833 a | |
| | 2 | 7.833b | 9.333a | 8.583 a | |
| Boron | | 8.000a | 8.417 a | | |

*Means with the same letter for every component and interaction do not differ significantly at the 5% level.*

### *Fruit Length (cm)*

The results in Table 2 showed that not applying fertigation with iron to the squash plant caused a significant increase in Fruit Length, reaching 13.525 cm, compared with the lowest value of 11.400 cm for the plant fertilized with Iron at a concentration of 2 mL L$^{-1}$. On the other hand, the Fruit Length also increased significantly when sprayed with 2 g L$^{-1}$ potassium fertilizer, reaching 12.900 cm, compared with the control at 12.025 cm. However, an increase in Boron concentration did not result in a significant increase when compared with the control.

The highest fruit length increased to 14.000 cm when fertigation with 0 g L$^{-1}$ Iron was combined with spraying 2 g L$^{-1}$ potassium, compared with the lowest value of 11 cm for the plant treated with 0 g L$^{-1}$ and sprayed with 2 g L$^{-1}$ potassium. However, the interaction between potassium and boron at concentrations of 2 g L$^{-1}$ and 0 mL L$^{-1}$ significantly increased fruit length, reaching 12.725 cm, compared with the lowest value of 10.800 cm for the plant treated with 0 g L$^{-1}$ potassium and 2 mL L$^{-1}$ Boron. Moreover, the interaction between Iron and boron in control plants significantly increases fruit length, reaching 15.125 cm, compared with the lowest value for the plant treated with 2 g L$^{-1}$ iron and 0 mL L$^{-1}$ boron, which is 10.850 cm.

The triple interaction among Iron, potassium and Boron fertilizers factors indicated that the plants which fertigation with 0 g L$^{-1}$ Iron, and spraying 2 g L$^{-1}$ potassium and 0 mL L$^{-1}$ Boron fertilizers gave the highest value of fruits length reached 15.500 cm, when compared with least value which reached to 10.250 cm for the plant treat with 2 g L$^{-1}$ for Iron and 0 g L$^{-1}$ potassium interacted with 2 mL L$^{-1}$ Boron.

Table 2. Effect of boron, potassium, iron, and their interaction on the length (cm) of the fruit of the squash plant.

| Iron g $L^{-1}$ | Potassium g $L^{-1}$ | Boron mL $L^{-1}$ | | Iron * potassium | Iron |
|---|---|---|---|---|---|
| | | 0 | 2 | | |
| 0 | 0 | 71.500 e | 75.500 d | 73.500 d | 80.000 a |
| | 2 | 88.500 a | 84.500 b | 86.500 a | |
| 2 | 0 | 81.000 bc | 83.000 b | 82.000 b | 79.250 a |
| | 2 | 75.500 d | 77.500 cd | 76.500 c | |
| Iron * Boron | 0 | 80.000 a | 80.000 a | potassium | |
| | 2 | 78.250 a | 80.250 a | | |
| Potassium * Boron | 0 | 76.250 b | 79.250 a | 77.750 b | |
| | 2 | 82.000 a | 81.000 a | 81.500 a | |
| Boron | | 79.125 a | 80.125 a | | |

*Means with the same letter for every component and interaction do not differ significantly at the 5% level.*

***Plant height (cm)***

The results in Table 3 showed that fertigation with Iron and spraying Boron on Squash plants at any concentration did not significantly increase Plant height compared with the control. Increasing potassium concentration to 2 g $L^{-1}$ in squash plants significantly increased plant height to 81.500 cm, compared with 77.750 cm in control plants.

Table 3. Effect of boron, potassium, iron, and their interaction on plant height (cm) of squash plant.

| Iron g $L^{-1}$ | Potassium g $L^{-1}$ | Boron mL $L^{-1}$ | | Iron * potassium | Iron |
|---|---|---|---|---|---|
| | | 0 | 2 | | |
| 0 | 0 | 4.300 a | 3.300 c | 3.800 a | 3.867 a |
| | 2 | 4.367 a | 3.500 bc | 3.933 a | |
| 2 | 0 | 3.433 c | 3.233 c | 3.333 b | 3.550 b |
| | 2 | 3.500 bc | 4.033 ab | 3.767 a | |
| Iron * Boron | 0 | 4.333 a | 3.400 b | potassium | |
| | 2 | 3.467 b | 3.633 b | | |
| Potassium * Boron | 0 | 3.867 a | 3.267 b | 3.567 b | |
| | 2 | 3.933 a | 3.767 a | 3.850 a | |
| Boron | | 3.900 a | 3.517 b | | |

*Means with the same letter for every component and interaction do not differ significantly at the 5% level.*

The highest plant height increased to 86.500 cm when fertigation of 0 g $L^{-1}$ Iron interacted with spraying 2 g $L^{-1}$ potassium, respectively, compared with the least value, which reached 76.500 cm for the plant treated with 2 g $L^{-1}$ Iron interacted with spraying 2 g $L^{-1}$ potassium. However, the interaction between potassium and boron caused a significantly increase in plant height, which reached 82.000 cm for plant spraying 2 g $L^{-1}$ interacted with fertigation with 0 mL $L^{-1}$ boron when compared with the control, which reached 76.250 cm. Additionally, the interaction between Iron and Boron did not show a significant increase.

The triple interaction among Iron, potassium, and Boron fertilizer factors indicated that the plants that were fertigated with 0 g $L^{-1}$ Iron and sprayed with 2 g $L^{-1}$ potassium and 0 mL $L^{-1}$ Boron fertilizers gave the highest value of plant height, reaching 88.500 cm, compared with the control, which reached 71.500 cm.

***Fruit weight (g)***

The results in Table 4 showed that fertigation with Iron on the squash plant did not significantly increase fruit weight. On the other hand, Fruit weight increased significantly when the plant was sprayed with 2 g $L^{-1}$ potassium fertilizer, reaching 100.588 g, compared with 82.375 g in the control. Whereas increasing boron concentration decreases fruit weight: at 2 mL $L^{-1}$, it reached 79.763 g compared with the control at 103.200 g.

Table 4. Effect of Boron, Potassium, Iron, and their interaction on fruit weight (g) of squash plant.

| Iron g $L^{-1}$ | Potassium g $L^{-1}$ | Boron mL $L^{-1}$ | | Iron * potassium | Iron |
|---|---|---|---|---|---|
| | | 0 | 2 | | |
| 0 | 0 | 14.750 ab | 11.350 de | 13.050 a | 13.525 a |
| | 2 | 15.500 a | 12.500 cd | 14.000 a | |
| 2 | 0 | 11.750 d | 10.250 e | 11.000 b | 11.400 b |
| | 2 | 9.950 e | 13.650 bc | 11.800 b | |
| Iron * Boron | 0 | 15.125 a | 11.925 b | potassium | |
| | 2 | 10.850 c | 11.950 b | | |
| Potassium * Boron | 0 | 13.250 a | 10.800 b | 12.025 b | |
| | 2 | 12.725 a | 13.075 a | 12.900 a | |
| Boron | | 12.988 a | 11.938 b | | |

*Means with the same letter for every component and interaction do not differ significantly at the 5% level*

The highest fruit weight increased to 115.200 g when the fertigation plant at a concentration of 0 g $L^{-1}$ Iron interacted with spraying 2 g $L^{-1}$ potassium, respectively, compared with the least value, which reached 58.800 g for the plant treated with 2 g $L^{-1}$ Iron interacted with spraying 0 g $L^{-1}$ potassium. Additionally, the interactions between potassium and Boron, and between iron and boron, did not differ significantly from the control at any concentration, with values of 104.500 g and 143.675 g, respectively.

The triple interaction among iron, potassium and boron fertilizers factors indicated that the plants which fertigation with 0 g $L^{-1}$ iron, and spraying 2 g $L^{-1}$ potassium, 0 mL $L^{-1}$ boron fertilizers gave the highest value of fruit weight reached 148.150 g, respectively, compared with least value which reached to 82.250 g for plant treated with 0 g $L^{-1}$ iron interacted with 2 g $L^{-1}$ and 2 mL $L^{-1}$ boron.

***Fruit diameter (cm)***

The results in Table 5 showed that fertigation OF iron on the squash plant at 2 g $L^{-1}$ caused a significant decrease in fruit diameter, which reached 3.550 cm when compared with the control. On the other hand, Fruit diameter increased significantly when the plant was sprayed with 2 g $L^{-1}$ potassium fertilizer, reaching 3.850 cm, compared with 3.567 cm in the control. Whereas increasing boron concentration decreases fruit diameter: at 2 $mL^{-1}$, it reached 3.900 cm, compared with 32.517 cm in the control.

The highest fruit diameter increased to 3.933 cm when fertigation with 0 g $L^{-1}$ iron was combined with spraying 2 g $L^{-1}$ potassium, compared with the lowest value of 3.333 cm for the plant treated with 2 g $L^{-1}$ iron combined with spraying 0 g $L^{-1}$ potassium. Additionally, the interaction between potassium and Boron significantly increases fruit diameters to 3.933 cm for the plant treated with a concentration of 2 g $L^{-1}$ potassium combined with 0 mL $L^{-1}$ boron, compared with the lowest value, which reached 3.267 cm for the plant treated with a concentration of 0 g $L^{-1}$ potassium combined with 2 mL $L^{-1}$ boron.

The triple interaction among Iron, potassium and boron fertilizer factors indicated that the plants that were fertigated with 0 g $L^{-1}$ Iron, and spraying 2 g $L^{-1}$ potassium, 0 mL $L^{-1}$ Boron fertilizers gave the highest value of fruit diameter reached 4.367 cm, respectively compared with least value which reached to 3.233 cm for plant treated with 2 g $L^{-1}$ Iron interacted with 0 g $L^{-1}$ and 2 mL $L^{-1}$ boron.

Table 5. Effect of boron, potassium, and iron, and their interaction, on fruit diameter (cm) of squash plants.

| Iron g $L^{-1}$ | Potassium g $L^{-1}$ | Boron mL $L^{-1}$ | | Iron * potassium | Iron |
|---|---|---|---|---|---|
| | | 0 | 2 | | |
| 0 | 0 | 139.200 ab | 72.700 cd | 105.950 a | 110.575 a |
| | 2 | 148.150 a | 82.250 c | 115.200 a | |
| 2 | 0 | 69.800 cd | 47.800 d | 58.800 b | 72.388 a |
| | 2 | 55.650 d | 116.300 b | 85.975 ab | |
| Iron * Boron | 0 | 143.675 a | 77.475 bc | potassium | |
| | 2 | 62.725 c | 82.050 b | | |
| Potassium * Boron | 0 | 104.500 a | 60.250 b | 82.375 b | |
| | 2 | 101.900 a | 99.275 a | 100.588 a | |
| Boron | | 103.200 a | 79.763 b | | |

*Means with the same letter for every component and interaction do not differ significantly at the 5% level*

## Discussion

The application of potassium (K), boron (B), and iron (Fe) has a substantial impact on the growth, productivity, and fruit qualities of *Cucurbita pepo* L. squash, according to the study's findings. The complex physiological roles of these nutrients and their interactions that influence crop performance are reflected in the reported impacts. The number of fruits per plant, plant height, fruit length, fruit weight, and fruit diameter were all improved by potassium, which was the most consistent parameter among all those measured. Tables 1 and 3 show that the number of fruits and plant height were significantly higher at (2 g $L^{-1}$) potassium application, which may be explained by the fact that K is essential for enzyme activation, photosynthesis, and osmotic regulation (Hasanuzzman *et al.,* 2018). The translocation of photosynthates from leaves to reproductive organs is known to be promoted by potassium (Lester *et al.,* 2010), thereby enhancing fruit set and fruit development. Moreover, it helps maintain turgor pressure and stomatal conductance, thereby improving gas exchange and water-use efficiency, which are essential for vegetative growth and biomass accumulation (Wang *et al.,* 2013). The results are in line with those reported earlier, which showed that K fertilization increased the production of pistillate flowers and fruit production in cucurbit crops (de Souza *at al.,* 2023; Budak and Güneş, 2023), Interestingly, the results for Boron and Iron showed a different trend, where the control treatments often resulted in better outcomes in fruit length, weight, and diameter (Tables 2, 4 and 5), especially when compared with the (2 mL $L^{-1}$ Boron) or (2 g $L^{-1}$) Iron fertigation. The concentrations used in this study suggest they may have been near or at the toxic limit for squash. Boron is needed for cell wall synthesis and reproductive development, with a narrow range between deficiency and toxicity (Rasheed, 2009). A decrease in fruit weight (Table 4) and fruit diameter (Table 5) was observed with Boron application, consistent with previous reports of B toxicity in squash, which causes yield loss due to physiological stress and metabolic dysfunction (South, 2021). In the same way, Fe is essential for chlorophyll biosynthesis and energy generation (Bacaicoa and García-Mina, 2009), and a high level of Fe may result in the production of Reactive Oxygen Species (ROS), which are responsible for oxidative damage to plant tissues and growth inhibition (Schmidt *et al.,* 2020). The fruits from the control plants had greater fruit length (Table 2) and diameter (Table 5), indicating that the Fe applied to the squash plants may have been a stress factor on the plants, or that the Fe application interacted with other plant essential nutrients in an antagonistic manner (Marschner, 2012). The interactions between the factors were found to be significant, especially that of Iron x Potassium. The interaction of 0 Iron 2 g $L^{-1}$ Potassium invariably resulted in the highest fruit number, fruit length, fruit height, fruit weight, and fruit diameter. This indicates a potentiated effect of Potassium, suggesting

that stress may have been induced by Iron at the concentration used, a phenomenon that occurs in the absence of iron. However, Potassium-Boron had a positive synergistic effect on the number of fruits and fruit length (Tables 1 and 2), with the highest value being obtained from 2 g $L^{-1}$ potassium and 2 mL $L^{-1}$ Boron. This suggests that Potassium can, at least partially, counteract the impact of Boron and/or that its two physiological functions, involved in sugar transport and reproductive development, are complementary. The fruit weight and diameter showed the highest values in the (2 g $L^{-1}$ potassium and 0 mL $L^{-1}$ Boron) interaction, indicating that K did not fully compensate for the negative effect of Boron on fruit size.

## Conclusion

Finally, it can be said that the productivity and vegetative growth of squash are greatly enhanced by a potassium application rate of 2 g $L^{-1}$. However, some fruit traits appeared to be inhibited by the application of Boron and Iron at the test rates, most likely due to toxicity or nutrient imbalance. The study's findings emphasize the need for optimal nutrient management and further research to determine the appropriate Boron and Iron concentrations for squash, given the specific conditions of the Kurdistan region.

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