Advancing Food Science, Quality Assurance, and Sustainable Innovation in Pakistan: A Strategic Vision Anchored in the Legacy and Future of Pakistan Society of Food Scientists and Technologists

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The world food system is experiencing a period of radical change with the complex combination of population growth, climatic uncertainty, technological turmoil, and consumer demands. The joint influence of these factors has enhanced the importance of food science and technology as an important solution to some of the most pressing problems of our time including food security, nutritional sufficiency, environmental sustainability, and economic stability. Issues like structural inefficiencies, low technological adoption, and regulatory shortfalls, are common and often remain unaddressed in developing countries, such as Pakistan. In this case, scientific institutions, professional societies, and academic platforms play a primary role of paramount importance in shaping the development of the country. It is a privilege and at the same time my duty as the President of the Pakistan Society of Food Scientists and Technologists (PSFST) to make a statement about our institutional heritage, as well as to provide a vision of the future of the Pakistan Journal of Food Sciences.

One of the earliest attempts to institutionalize the field of Food Science and Technology in Pakistan is the Pakistan Society of Food Scientists and Technologists, which was established in 1981. Its foundation was a landmark in the development of food science as an independent and critical science, the one that unites agriculture, chemistry, microbiology, engineering, and nutrition. The reinstatement of the PSFST in the year 1991 further enhanced its mandate, which enabled it to diversify its operations and enhance its status as one of the professional bodies in the country. PSFST has, over the decades, developed into a vibrant platform, bringing together academic, industry, government, and civil society in a platform that ensures collaboration and excellence in food science and technology.

One of the main characteristics in the development of PSFST has been its focus on aligning the national activities with the standards and best practices in the world. This has been majorly facilitated by its membership in the Institute of Food Technologists (IFT), USA, which has availed international expertise, resources, and networks. This association has helped with knowledge sharing and best practices enabling Pakistani professionals to stay updated with the current global trends in the field of food science. It has equally increased the credibility and the visibility of PSFST, thus making it a major stakeholder in the global scientific society.

Since its establishment, PSFST has been on a clear mission, to advance food science and technology for the growth and development of our country. The latter has been accomplished through a wide range of operations, including the organization of conferences, seminars, workshops, and training programs. Such programs have presented tremendous opportunities for knowledge sharing, capacity building, and networking. They have also assisted in the dissemination of new ideas and innovations, which have assisted in the direction of defining the food sector in Pakistan.

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One of the most significant contributions that PSFST has made was its influence on the food policy and regulation. The society has been keen to engage with the policy makers on issues of food safety and quality due to its critical importance in this industry. It is worth mentioning that PSFST has advocated for the establishment of the Punjab Food Authority (PFA), a body towards ensuring food safety and hygiene in the province. This achievement underscores the capacity of the society to implement scientific knowledge into feasible policy outcomes, thereby positively impacting human health and consumer protection.

Other than policy advocacy, PSFST has made remarkable investment in education and capacity building as well. The society's collaboration with Global Alliance to Nutrition (GAIN) in screening and curriculum design of food safety programmes indicates its concern with the academic and professional training. These programs have also led to the production of a new breed of food scientists who are able to cope with the challenges of the current times using the knowledge and skills required by the industry and international standards, and by ensuring that the curricula are adjusted to the needs of the industry and international standards.

The other fields in which the society has made contributions are research and innovation, and these have been done through its flagship journal, the Pakistan Journal of Food Sciences. Since its revival in 1991, the journal has been an invaluable tool of scientific knowledge dissemination in which original research, review, and technical report publications have appeared in an extremely wide range of subjects. The new format of the journal denotes a new meaning of mission in enhancing its academic and editorial quality and global outlook. The journal will adhere to the values of transparency, integrity, and excellence, contributing to the worldwide dissemination of scientific knowledge and will be among the most popular in the field.

PSFST has had an interest in professional development and networking. The society has conducted numerous national conferences, seminars, and expos where different stakeholders in different sectors have been brought together. The events have facilitated the exchange of ideas, collaboration, and provided a platform where innovations can be marketed. One of the most outstanding moments for the society was the annual conference held in 2000, in which the then President of Pakistan, Mr. Rafique Tarrar, was the Chief Guest. Other than illuminating the national value of the input of PSFST, the event also established awareness of food science contributions in the general developmental agenda.

PSFST has also been keen on international partnerships, as it has conducted seminars and workshops with international partners like the Malaysian Palm Oil Board (MPOB). The society has been able to lead the new trends and technologies because it participated in the key industry exhibitions. In addition, PSFST has developed great connections with the top industry players, Nestle, Engro, Dawn Foods, Vita, Rafhan Maize, National Foods, Mitchells, PepsiCo, Coca-Cola, Merit, and Pizza Hut among others. These partnerships have provided students and professionals with a great chance to develop internships, training, and careers.

In addition to its scholarship and professional activities, PSFST has been very socially responsible. There are community activities in which the society has participated actively, such as the flood relief programs, whose purpose is to help the impacted people. The community nutrition work, especially the preparation of educational manuals for school teachers, is indicative of its concern to enhance the health of the population and create awareness on the issue of nutrition at grassroot level. These programs emphasize a bigger picture of society in giving back not only to the development of science but also to societal welfare.

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Despite the accomplishment of these success stories, the food industry in Pakistan has yet to be on its feet. The country has massive agricultural potential but is unable to compete in the global markets because of the inefficiencies in the post-harvest processing, value addition, and bad infrastructure. The adoption of modern quality management systems is not homogeneous yet, and the use of advanced technologies remain in its early stages. These issues can only be addressed by using a holistic and well-coordinated approach that includes policy reforms, technological development, and capacity building.

This change lies in the management of quality. The introduction of food safety, consistency, and competitiveness is possible with the implementation of internationally accepted standards such as ISO 9000 and Hazard Analysis and Critical Control Points. These systems provide methodological approaches to identify risks, optimization, and quality in processes across the value chain. In the scenario of the food industry in Pakistan, it is not only a regulatory choice, but also a strategic choice because then the industry can access the international market as well as win the confidence of the consumers.

Another factor that matters in the future of the food industry is technological innovation and development. The new technologies, such as precision agriculture, biotechnology, and digital traceability systems, offer new avenues for increasing productivity as well as improving the quality and transparency. However, there is the cost of these technologies in terms of investment, infrastructure, and technical skills. PSFST is important in that direction as it allows the academia and industry to collaborate, along with providing assistance in formation of favorable policies, research and development.

Sustainability is one of the concepts of modern food systems. Food production and food processing have environmental aspect that require a shift towards more resource-efficient and environmentally responsible practices. This is through food waste reduction, optimization of water and energy use, and sustainable packaging. PSFST can also contribute to the development of resilience food system through integrating the notion of sustainability in its programs to assist in balancing between economic, environmental, and social aspirations.

The development of human resources remains one of the essential drivers for progress in food science and technology. The modern world consists of multidisciplinary problems that require a multidisciplinary workforce. PSFST has been playing a major role in this field through its training programs, academic partnerships, and student interaction programs. Yet, one should say that there is a necessity to give more impetus to these activities by matching educational programs to the needs of the industry and encouraging continuous professional growth.

Governance and policy frameworks also play a major role in ensuring that the transformation of the food sector is facilitated. Good policies can provide a facilitating atmosphere for innovation, investment, and quality. This involves setting regulatory standards, financial incentives, and sponsoring research. The cooperation between the state, higher education institutions, and the business community is needed to create coherent plans and acchieve sustainable results.

The rejuvenated Pakistan Journal of Food Sciences is seen as a driver in the achievement of these aims. The journal intends to increase its impact on global knowledge by publishing high-quality and peer-reviewed research and advocating interdisciplinary studies. It aims to offer an avenue to discuss the most pressing problems in the field of food science and to promote communication among the stakeholders. By so doing, it will be not only a knowledge repository but also a driver of innovation and policymaking.

In prospect, the future of the food industry in Pakistan is based upon how we can build upon the legacy of institutions like PSFST. The Society has been resilient, adaptable, and focused on excellence since its registration in 1981 and revival in 1991. It has high prospects for improving policy advocacy, research, professional development, and community engagement. Going forward, there is an urgent need to enhance institutional capabilities, foster research quality, and connect with international networks.

To sum it up, the PSFST is source of hope and a gateway of development for Food Scientists and Technologists in Pakistan. Further initiatives that it is undertaking to promote scientific growth, increase the standards of quality, and accelerate innovation are vital in ensuring the emergence of a safe, sustainable, and competitive food industry. A stronger PSFST will lead to a stronger, safer, and more innovative food industry in Pakistan. By working together, sharing a vision, and staying dedicated, we will be able to turn obstacles into opportunities and create a strong food system that will sustain the needs of the current and future generations.

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Role of Plant-Derived Antioxidants in Improving Shelf Life of Fruit Juices: A Mini Review

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ABSTRACT

Fruit juices are widely consumed due to their nutritional value, taste, and convenience, but they are highly liable to quality deterioration during processing and storage. Oxidative reactions are a major cause of browning, flavor loss, nutrient degradation, and reduced shelf life in juices. Plant-derived antioxidants, obtained from fruits, vegetables, herbs, and agro-industrial by-products, have emerged as effective natural alternatives to synthetic preservatives. These compounds, including phenolics, flavonoids, and carotenoids, exhibit strong antioxidant activity and can improve juice stability without affecting sensory quality. This review discusses the sources of plant-derived antioxidants, extraction methods such as ultrasound-assisted extraction, and their application in fruit juices. The incorporation of natural antioxidants not only extends shelf life and preserves product quality but also supports sustainability by enabling the valorization of food processing by-products. Overall, plant-derived antioxidants offer a safe, effective, and eco-friendly strategy for enhancing the storage stability of fruit juices.

Keywords: Fruit juice, Plant-derived antioxidants, Shelf life, Oxidation, Natural preservatives, Food quality

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Introduction

Fruit juices are popular all over the world because of their convenient, nutritious, and refreshing flavor. Fruit juices are rich sources of minerals, vitamins, and bioactive compounds that promote human health (Bhardwaj et al., 2014). Nevertheless, they are highly susceptible to quality deterioration during processing and storage, with oxidative reactions being a major factor that limits their shelf life in the juice industry (Roobab et al., 2018).

Fruit juices undergo several unfavorable changes as a result of oxidative degradation, such as browning, flavor loss, decreased nutritional value, and the development of unpleasant odors (Jia et al., 2024). Synthetic antioxidants have historically been employed to manage these alterations and enhance stability. Consumer demand for natural and clean-label products has surged in recent years due to worries about the safety and possible health hazards of synthetic additives (Nikoo and Gavlighi, 2022).

Antioxidants derived from plants have therefore drawn a lot of interest as organic substitutes for artificial preservatives. These antioxidants, which have potent antioxidant qualities, are derived from fruits, vegetables, herbs, and agro-industrial by-products (Lourenço et al., 2019). This mini review highlights the sources, extraction techniques, and uses of plant-derived antioxidants in extending the shelf life of fruit juices.

Oxidative Deterioration in Fruit Juices

Oxidation is a primary factor contributing to the deterioration of fruit juice quality. During storage, juice quality declines as a result of both enzymatic and non-enzymatic oxidation processes (Singh and Sharma, 2017). Enzymatic browning, largely driven by polyphenol oxidase, accelerates the oxidation of phenolic compounds, leading to color changes and reduced visual appeal (Sui et al., 2023).

Important juice ingredients, such as ascorbic acid, pigments, and flavor compounds, are impacted by non-enzymatic oxidation. These reactions are accelerated by exposure to light, oxygen, and high storage temperatures (Zhu et al., 2023). In addition, ascorbic acid oxidation lowers nutritional value and starts additional oxidative reactions that have a detrimental effect on the stability of the juice as a whole (Yin et al., 2022). These oxidative changes lead to decreased consumer acceptance and shortened shelf life of fruit juices. Therefore, the control of oxidation is essential to maintain quality and extend the storage life of juice products.

Plant-Derived Antioxidants and Their Mechanism of Action

Numerous naturally occurring substances, including phenolic acids, flavonoids, tannins, and carotenoids, are classified as plant-derived antioxidants. By scavenging free radicals, chelating metal ions, and preventing oxidative chain reactions, these substances demonstrate antioxidant activity (Akbari et al., 2022).

Phenolic compounds are particularly effective antioxidants due to their ability to donate electrons or hydrogen atoms to neutralize reactive oxygen species. Their antioxidant efficiency depends on factors such as chemical structure, concentration, and interactions with the food matrix. Owing

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to their natural origin and inherent bioactivity, plant-based antioxidants are generally considered safer than synthetic alternatives (Ahmad et al., 2025).

Sources of Plant-Derived Antioxidants

Fruits, vegetables, herbs, and spices are abundant sources of plant-based antioxidants. In addition, agro-industrial by-products such as fruit peels, seeds, and pomace have recently attracted attention as cost-effective and sustainable sources of antioxidants. Despite their high content of bioactive compounds, these materials are often discarded during food processing, representing a largely underutilized resource (Saini et al., 2025). It has been observed that fruit peels, such as those from citrus fruits, apples, and pomegranates, have higher concentrations of phenolic compounds than the fruit's edible parts. Using these by-products promotes waste reduction and sustainable food processing methods in addition to offering useful sources of antioxidants.

Extraction of Antioxidants from Plant Materials

The extraction method plays a critical role in determining the yield and activity of plant-derived antioxidants. Conventional extraction techniques, such as solvent extraction, are commonly used but often require long extraction times and large amounts of solvents. These methods may also lead to the degradation of heat-sensitive compounds (Geow et al., 2021). To overcome these limitations, advanced extraction techniques have been developed. Ultrasound-assisted extraction is one such method that enhances mass transfer through acoustic cavitation, leading to improved release of antioxidants from plant tissues (Siddique et al., 2025). This technique offers advantages such as reduced extraction time, lower solvent consumption, and improved extraction efficiency. The selection of an appropriate extraction method depends on the type of plant material and the intended application of the extracted antioxidants in food systems.

Application of Plant-Derived Antioxidants in Fruit Juices

The incorporation of plant-derived antioxidants into fruit juices has been shown to effectively improve oxidative stability during storage. These antioxidants help in delaying browning reactions, maintaining color, and preserving flavor and nutritional quality (Manessis et al., 2020). Importantly, the use of plant-based antioxidants does not negatively affect sensory attributes when applied at appropriate concentrations (Djordjević et al., 2024). This makes them suitable for use in commercial juice products. The growing demand for clean-label beverages has further increased interest in the use of natural antioxidants in fruit juice formulations. Their application aligns with consumer preferences for minimally processed foods free from synthetic additives.

Challenges and Future Perspectives

Although plant-derived antioxidants hold significant promise for enhancing the quality and shelf life of fruit juices, several challenges hinder their widespread industrial application. The composition and concentration of antioxidants can vary widely depending on the plant source, growing conditions, and processing methods, leading to inconsistent efficacy (Akhi et al., 2025).

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Moreover, their stability during storage can be affected by factors such as pH, temperature, light exposure, and interactions with other juice components, potentially reducing their antioxidant activity over time. In some cases, the incorporation of plant antioxidants may also alter the sensory attributes of juices, such as taste, color, or aroma, which could affect consumer acceptance.

To address these challenges, it is essential to optimize extraction techniques, including the use of green solvents, enzyme-assisted extraction, and novel technologies like ultrasound- or microwave-assisted methods, to maximize yield and bioactivity. Additionally, standardized application protocols should be developed to ensure consistent antioxidant performance across different juice formulations. Future research should also explore encapsulation and nano-delivery systems to enhance the stability and controlled release of plant antioxidants. Finally, comprehensive economic and life-cycle assessments are needed to evaluate the feasibility, scalability, and environmental impact of integrating plant-derived antioxidants into industrial juice production, paving the way for sustainable and health-promoting functional beverages.

Conclusion

Plant-derived antioxidants play a vital role in enhancing the shelf life, nutritional quality, and sensory properties of fruit juices by mitigating oxidative deterioration. Their natural origin, bioactivity, and safety profile make them attractive alternatives to synthetic preservatives, which are often associated with health concerns. The utilization of plant-based sources, particularly agro-industrial by-products such as fruit peels, seeds, and pomace, not only adds functional value to juices but also contributes to sustainable food production by reducing waste and promoting circular economy practices. Advances in extraction technologies, encapsulation methods, and controlled-release systems are expected to further improve the stability, bioavailability, and efficacy of these natural antioxidants in juice formulations. Future research should also focus on optimizing processing conditions, evaluating long-term storage effects, and conducting comprehensive economic and environmental assessments to enable large-scale industrial adoption. Overall, plant-derived antioxidants represent a safe, sustainable, and effective strategy for developing functional fruit juices with extended shelf life and enhanced health benefits.

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Impact of Poor Dietary Habits on Academic Performance among Female Undergraduate Students in Lahore, Pakistan

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ABSTRACT

Dietary habits are widely reported as a determinant of students' health, limited research has been conducted in Pakistan on how poor dietary habits affect academic performance. This study investigates the impact of poor dietary habits of female undergraduate students on academic performance. A self-structured questionnaire assessing dietary habits and academic outcomes, such as self-reported GPA, Overall Academic Performance Rating (OAPR), and an Academic Performance Index (API) assessing focus, attentiveness, alertness, recall, task completion, and satisfaction with results, was filled by 384 participants in a cross-sectional survey at the University of Management and Technology, Lahore. The results showed a high prevalence of meal skipping practice, especially breakfast (71.9%), as well as excessive consumption of junk food (53.6%) and snacks (59.6%). The daily consumption of fruits (3.9%) and vegetables (2.9%) was extremely low. GPA, OAPR, and API were all significantly correlated with poor dietary habits, according to chi-square analyses. Poor dietary habits were significantly negatively correlated with GPA ($\rho = -0.479$, $p < 0.001$), OAPR ($\rho = -0.420$, $p < 0.001$), and API ($\rho = -0.390$, $p < 0.001$), according to Spearman correlations. Skipping lunch and breakfast as well as substituting meals with snacks or beverages were consistent negative predictors in multiple regression analyses. Higher meal frequency positively predicted all academic indicators, while fast food consumption was associated with lower GPA and OAPR. In conclusion, poor dietary habits were found common in students and closely linked to lower academic achievement. These results highlight the need of institutional strategies and nutrition education initiatives to encourage better eating habits and academic success.

Keywords: Dietary habits, Academic performance, Undergraduate female students, GPA, Overall academic performance rating.

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INTRODUCTION

Academic success strongly influences socioeconomic status, career prospect and overall health (Burrows et al., 2017). University education is considered as essential for both individual and national development in developing nations like Pakistan (Kosar, 2024). However, students deal with a number of difficult issues, such as pressure to perform well academically, lack of resources, and lifestyle changes that frequently result in unhealthy eating habits (Mulaudzi, 2023). Unhealthy eating habits like skipping meals, relying on fast food, sugary snacks and drinks, and irregular meal schedules are common among students. These behaviors are associated with fatigue, decreased cognitive functioning, micronutrient deficiencies, and weight gain, all of which may have a detrimental impact on academic performance (Verulava and Devnozashvili, 2021; Abraham et al., 2018; Fazal and Kazimi, 2019). According to research, eating breakfast is positively correlated with memory, focus, and problem-solving abilities, whereas high consumption of fast food and sugar-sweetened beverages is linked to poor involvement in the classroom and a lower GPA (Peña-Jorquera et al., 2021; Saad et al., 2024; Hammoudi Halat et al., 2023; Azzura et al., 2025). Few studies have looked at the connection between poor eating habits and academic performance among Pakistani female undergraduates, a population that is especially vulnerable because of cultural, social, and lifestyle factors, despite mounting evidence worldwide (Shabbir et al., 2021; Tanveer et al., 2022).

Objective: This study aims to assess the prevalence of poor dietary habits and investigate their impact on academic performance among female undergraduate students at the University of Management and Technology, Lahore.

Hypothesis: Poor dietary habits significantly affect academic performance among female undergraduate students.

MATERIALS & METHODS

384 female undergraduate students at the University of Management and Technology, Lahore, participated in this cross-sectional survey. Students in their second to fourth years who gave their consent were selected through random sampling to be participants. The university's Institutional Ethics Committee granted ethical approval before conducting the survey. A structured self-administered questionnaire comprising five sections was used to gather data including questions about academic performance, dietary patterns, frequency of unhealthy and healthy foods, and demographics. Meal frequency, skipping, and replacement with snacks, consumption of fast food, and consumption of fruits, vegetables, dairy, and water were among the dietary practices evaluated. Academic performance was measured by self-reported GPA, the Overall Academic Performance Rating (OAPR), and a six-item Academic Performance Index (API) that assessed focus, attentiveness, mental alertness, recall, task completion, and satisfaction.

As shown in Figure 1, the healthy food items were reverse-coded, and dietary frequency items were scored so that higher values indicated worse habits. Higher values indicated better performance when API scores were summed up. Descriptive statistics, Chi-square tests, Spearman correlations, and linear and multiple regressions were used in SPSS v26 data analysis to look at relationships and predictive effects of dietary practices on GPA, OAPR, and API. The threshold for statistical significance was set at $p < 0.05$.

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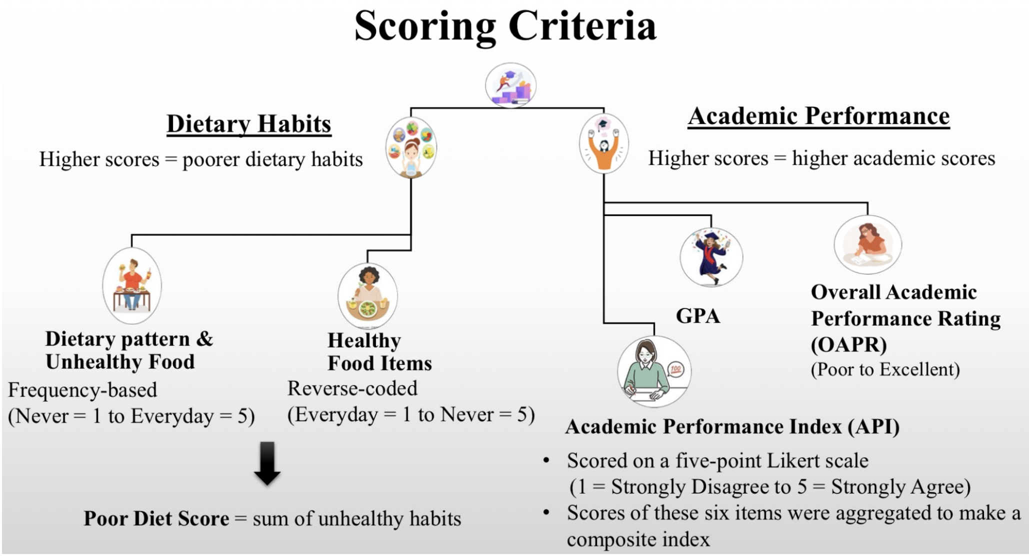

Figure 1: Scoring criteria of the questionnaire

RESULTS

Out of 384 respondents, 63.3% (n=243) weighed between 40 and 50 kg. Of them, 27.9% (n = 107) weighed between 51 and 60 kg, and 4.7% (n = 18) weighed between 61 and 70 kg. Just 1.8% (n = 7) of the students weighed more than 70 kg, and 2.3% (n = 9) weighed less than 40 kg. 68.8% of female university students in the study reported being between 5'0" and 5'5" tall, while 24% reported being between 5'6" and 5'9" tall. Just 7.3% of them were smaller than 5'0".

Furthermore, 99.2% of the 384 participants were single, suggesting that unmarried undergraduate students made up the majority of the sample. Fourth-year students made up the majority of study participants (45.6%) followed by third-year students (30.2%) and second-year students (24.2%). Only 2.9% of respondents lived in hostels with mess facilities, compared to 57.8% who were day scholars and 39.3% who lived in hostels without mess facilities. According to the income distribution, 44.3% of the participants' families made between 100,000 and 150,000 PKR, while 35.2% made between 51,000 and 100,000 PKR. Very few had family incomes of less than 50,000 PKR (1.3%) or more than 200,000 PKR (2.1%), and a smaller percentage fell into the 150,000–200,000 PKR group (17.2%). This implies that the majority of students were from middle-class families.

The results of the dietary pattern analysis showed notable patterns in the eating habits of the participants. The majority of female students (63.3%) (n = 243) thought that breakfast was the most important meal, followed by lunch (27.3%) (n = 105) and dinner (n = 36). The majority of participants (44.8%) (n = 172) reported eating two to three meals a day, but 31.8% (n = 122) only ate one to two meals, a sign of inadequate nutrition. Breakfast was one of the most frequently skipped meals, with 31.5% (n = 121) skipping it once or twice a week, 40.4% (n = 155) skipping it three to four times a week, and 19.3% (n = 74) never skipping it. 46.1% (n = 177) skipped lunch once or twice a week, 37% (n = 142) skipped it three to four times a week, and 11.5% (n = 44) never skipped lunch.

According to the study, 63.5% of students skip dinner every week and 4.9% of students skip

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lunch on a regular basis. Lack of time (41.7%) and academic workload (24.7%) are the main causes of meal skipping, indicating that lifestyle pressures have a greater impact than financial limitations. Remarkably, 53.4% of students believe that skipping meals has a detrimental effect on their academic achievement. 59.6% of students substitute snacks for meals 1–2 times per week, indicating irregular eating habits. The results point to a worrying trend of meal skipping and reliance on unhealthy food substitutes, which could have a negative impact on students' academic performance and health.

Fast food, including burgers and fries, was reported to be consumed once or twice a week by 49.5% (n = 190) and three to four times a week by 25% (n = 96). Just 6% (n = 23) said they never ate fast food, while 17.7% (n = 68) said they did so five or six times a week. Just 1.8% (n = 7) reported daily consumption. Chips and samosas, among other fried snacks, were also frequently eaten, with 37.8% (n = 145) consuming them three to four times per week and 49% (n = 188) once or twice per week. Interestingly, 4.2% (n = 16) reported never eating fried snacks, 8.9% (n = 34) reported eating them five to six times a week, and just one person (0.3%) reported eating them every day. Packaged sugary snacks were consumed three to four times per week by 28.9% (n = 111), once or twice per week by 58.6% (n = 225), and never by 6.8% (n = 26). With 30.2% (n = 116) consuming them one to two times per week and 52.3% (n = 201) consuming them three to four times per week, sugary drinks constituted a substantial portion of students' diets. While 0.5% (n = 2) reported daily consumption, a tiny percentage, 2.3% (n = 9) did not drink sugary drinks. Over half (n = 207) 53.9% consumed desserts like cakes and ice cream one to two times per week, while 21.6% (n = 83) consumed them three to four times per week. Dessert consumption on a daily basis was found uncommon (1.8%, n = 7) and 11.2% (n = 43) said they never ate dessert. It's interesting to note that 59.9% (n = 230) of students reported feeling guilty after consuming unhealthy food, whereas 40.1% (n = 154) did not. This suggests that students continue to eat unhealthy food even though they are aware of the possible health risks.

43% of participants reported eating fresh fruits one to two times a week, while 40.6% reported eating them three to four times a week. Just 3.9% (n = 15) reported eating fruits every day, and 4.9% (n = 19) said they never did. One third of respondents (n = 130) 33.9% reported eating fresh vegetables five to six times per week, while over half (n = 220) 57.3% reported eating them three to four times per week. No respondents reported never eating vegetables. Of the students, 47.1% (n = 181) reported consuming dairy products one to two times a week, whereas 18% (n = 69) said they never ate dairy. Concerns about water intake were raised because only 2.1% of students (n = 8) consumed the recommended amount of water each day, while the majority (65.4%) (n = 151) did so three to four times per week. Overall, there was insufficient adherence to hydration guidelines, despite some regular intake. Only a small percentage of students acknowledged poor eating habits (n = 63) 16.4% with over half rating their eating habits as average (n = 210) 54.7% and 28.9% (n = 111) as good. This indicates the general perception of moderate dietary quality among students.

The fifth section examined the academic performance of female undergraduate students. The majority of participants (n = 129, 33.6%) had GPAs between 3.0 and 3.49, with 2.5–2.99 (n = 118) 30.7% coming in second. Furthermore, no student reported a GPA below 2.0, with 72 (18.8%) having a GPA of 2.0–2.49 and 65 (16.9%) reaching 3.5–4.0. According to self-evaluations, 40.6% of respondents thought their performance were good, 34.4% thought it was average, and only 6.8% thought it was excellent. Interestingly, 14.1% of respondents thought their performance was below average and 4.2% thought it was poor. The study revealed a range

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of academic behaviors: while the majority either agreed (n = 150) 39.1% or remained neutral (n = 96) 25%, one-third (n = 123) 32% disagreed that they were attentive in lectures. Slight agreement on attention levels is suggested by the mean score (M = 3.08, SD = 0.93). 35.2% of respondents disagreed with the significance of concentration when studying, and the mean score (M = 3.24, SD = 1.05) showed varying levels of focus. Additionally, 39.1% of respondents disagreed that mental alertness is necessary for academic tasks; the mean (M = 2.95, SD = 0.88) reflects this disagreement. During exams, a considerable portion had trouble recalling information (M = 2.81, SD = 0.93) and the mean (M = 2.69, SD = 0.85) indicated a tendency toward difficulty in task completion. Although 29.7% of respondents agreed and 13.8% strongly agreed that academic results were satisfactory, many others expressed doubt or discontent. Overall, the results show that students have a moderate level of focus and attentiveness, but they also show notable difficulties with memory, task completion, and alertness, which may be related to the study's dietary and lifestyle factors.

Variable	Association with Dietary Habits	Association with Academic Performance	Statistical Significance (p)
Family Income	Positive correlation (ρ = .120) → Higher income = better diet	No significant effect	p = 0.019
Dietary Habits vs API	—	Negative correlation (ρ = –0.394) → Poor diet = low API	p = 0.000
Dietary Habits vs GPA	—	Negative correlation (ρ = –0.479) → Poor diet = low GPA	p = 0.000
Dietary Habits vs OAPR	—	Negative correlation (ρ = –0.420) → Poor diet = poor self-rated performance	p = 0.000

Table 1: Correlation Analysis Summary

The study investigated the relationship between students' dietary habits and sociodemographic traits using the chi-square test and Spearman's correlation. Age, residential status, weight, and eating habits did not significantly correlate with each other, according to the results, indicating that these variables had no influence on students' eating habits. On the other hand, dietary habits and family income were found to be positively correlated, with wealthier students generally having healthier diets as shown in Table 1. Age, weight, and residential status had little effect on academic performance, suggesting that there is no significant relationship between these variables and academic results.

The Academic Performance Index (API) and dietary practices were found to be significantly correlated, with students who had better eating habits consistently achieving higher performance metrics. Particular results showed that a considerable proportion of students with poor eating habits (72.5%) were in the low performance category, whereas 43.3% of students with good eating habits were in the high performance group. A strong correlation between dietary practices and academic performance was confirmed by statistical analyses, which included a chi-square score of 70.646 ($p < 0.05$).

Additionally, the study found a moderately negative correlation (Spearman's rho = -0.479) between poor eating habits and lower academic achievement. While students with poor diets were concentrated in lower GPA ranges, those with healthy eating habits typically achieved GPAs between 3.0 and 3.49 (52.5%). A strong correlation between poor eating habits and

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GPA outcomes was found by additional chi-square analysis (chi-square score = 116.988, $p < 0.001$). According to self-rating assessments, students who followed a healthy diet rated their performance highly (54.6% good and 9.9% excellent), supporting the conclusion that better eating habits lead to improved academic performance. In conclusion, the study establishes a statistically significant correlation between eating habits and academic outcomes, rejecting the null hypothesis.

Table 2: Impact of Poor Dietary Habits on Academic Performance (Linear Regression)

Academic Indicator	β	R^2	**p-value**
GPA	-0.460	0.212	0.000
OAPR	-0.404	0.163	0.000
API	-0.390	0.152	0.000

Interpretation: Poor diet predicts ↓ GPA, ↓ self-rated performance, ↓ cognitive performance.

As shown in Table 2, the effect of poor eating habits on academic performance metrics, including GPA, academic performance index (API), and overall academic performance rating (OAPR), among female undergraduate students was examined using linear regression analysis. The findings showed significant negative correlations: lower GPA was predicted by poor eating habits (F(1,382) = 102.71, $p < 0.001$; R^2 = 0.212), with a regression coefficient of B = -0.460. Dietary practices also had a negative impact on API, accounting for 15.25% of the variance (F(1,382) = 68.38, $p < 0.001$; R^2 = 0.152, $\beta = -0.390$), and predicted OAPR with an explained variance of 16.3% (F(1,382) = 74.49, $p < 0.001$; R^2 = 0.163, $\beta = -0.404$).

Table 3: Multiple Regression Analysis Predicting Academic Performance from Dietary Habits

Dietary Habits	**Academic Performance (β)**		
	GPA	**OAPR**	**API**
Skipping breakfast	-0.150	-0.129	-0.147
Skipping lunch	-0.172	-0.033	-0.172
Skipping dinner	0.105	-0.014	0.046
Replacing meals with snacks	-0.243	-0.204	-0.272
Fast food intake	-0.174	-0.155	0.017
Meal frequency	0.182	0.130	0.174
R^2	0.257	0.163	0.215

Note: p-values: GPA: breakfast p=0.001, lunch p=0.004, snacks p=0.000, fast food p=0.001, meal freq p=0.000; OAPR: breakfast p=0.009, snacks p=0.000, fast food p=0.006, meal freq p=0.008; API: breakfast p=0.002, lunch p=0.006, snacks p=0.000, meal freq p=0.000.

With variances of 25.7%, 16.3%, and 21.5% respectively, multiple regression analyses found that skipping breakfast, lunch, and substituting meals with snacks or fast food were significant predictors of lower GPA, OAPR, and API as shown in Table 3. GPA results were significantly impacted by skipping breakfast ($\beta = -0.150$), skipping lunch ($\beta = -0.172$), and substituting

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meals ($\beta = -0.243$). On the other hand, the quantity of meals consumed daily was a positive predictor of GPA ($\beta = 0.182$). Skipping dinner and consuming sugary foods were not statistically significant among the less significant variables. Overall, the results show that eating more meals is positively correlated with academic success, while dietary habits like skipping meals are harmful to academic performance.

DISCUSSION

University students' eating habits are a significant factor in determining their health. The current study looked into the impact of poor dietary habits of female undergraduate students on their academic performance. In order to investigate relationships between eating habits and academic results, a total of 384 participants were involved, and their demographic traits, dietary habits, and academic achievement were examined. The findings provide strong evidence that dietary patterns, particularly meal skipping, meal replacement with snacks, and fast-food consumption, are significantly associated with lower academic performance, including GPA, Academic Performance Index (API), and overall academic performance rating (OAPR), both in terms of objective and self-reported outcomes. Socio-demographic characteristics including gender and socioeconomic position, have been demonstrated to have an impact on academic achievement in specific fields of study (Okioga, 2013). Interestingly, in this study, socio-demographic variables such as age, weight, and residence showed no significant association with dietary habits or academic performance but financial status did impact positively both dietary habits and academic performance.

The findings of this study revealed that breakfast (63.3%) was regarded as the most essential meal, yet, it was also the most frequently skipped meal, with 40.4% skipping 3–4 times per week and 8.1% skipping 5–6 times per week, furthermore, lunch and dinner skipping were also common, with 46.1% skipping lunch 1–2 times per week and 63.5% skipping dinner 1–2 times per week, due to lack of time, academic workload, and poor meal planning. A meta-analysis of 24 observational studies found that youths who skip breakfast have about double the odds of poorer academic performance than those who regularly eat breakfast (Seura et al., 2025). Similarly, the regression results of this study revealed that skipping lunch and then breakfast had consistent and significant negative effects on GPA and API (concentration, alertness, recall and satisfaction), while dinner skipping showed no meaningful impact. 53.4 percent of the female students felt that skipping meals had an impact on academic performance, reflecting the importance of nutrition in learning. A study showed that students who frequently consume a filling breakfast just before a cognitive task perform better than those who don't (Peña-Jorquera et al., 2021). All this data suggest that early day meals may be especially important for better focus, and learning efficiency.

A majority (59.6%) of the female students said that they only consume snacks once or twice a week, while fifty one percent said they only have tea or coffee in place of proper meals and fifty three percent said they only consume processed or fast food once or twice a week. These patterns point to nutrient deficiencies and irregular eating, which can negatively affect vitality, focus and overall health. A cross sectional study was conducted on Mangaluru students to examine the unhealthy snacking behaviors with 865 students. Breakfast was the most common meal skipped (26.2%), and a large percentage of students (71.9%) who skipped breakfast also snacked (Mithra et al., 2018). The frequent replacement of snacks for meals was also linked with less

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focus, fatigue and lower GPA in exams, according to the study conducted among Malaysian undergraduates (Aquino et al., n.d.). Similarly, in the current study, meal skipping ($\beta = -0.153$ to -0.196) and meal substitution with snacks and drinks ($\beta = -0.202$ to -0.275) were among the strongest negative predictors of GPA, API, and overall academic performance rating, shown in multiple regression analysis results. These results of the study highlight the importance of scheduled, balanced meals for better cognitive and learning outcomes, indicating that replacing the meals with snacks or beverages has a stronger negative impact on academic performance than meal skipping alone.

A recent study conducted in Lahore among the medical students showed that about thirty six percent of the students frequently eat fast food and twelve percent use sugar sweetened beverages. Salty snacks (77%) and carbonated drinks (67%) were the most frequently consumed item (Maqbool et al., 2024). Similarly in our study fast food and sugary snack consumption were also common, with nearly half (49.5%) consuming fast food 1–2 times per week, 25% consuming it 3–4 times per week and 52.3% drinking sugary beverages 3–4 times weekly. Packaged sugary snack consumption was also prevalent, with 28.9% reporting intake 3–4 times weekly, indicating both frequent consumption and limited awareness about nutrition. Another study in Pakistan using the theory of planned behavior showed that intention, popularity and peer norms strongly influence fast-food consumption among college students (Sajjad et al., 2023). In line with Chai and Cheah (2024), who reported that students at University Utara Malaysia with higher academic performance were less likely to consume fast food, the present study also found that fast-food intake negatively impacts academic outcomes. However, while the Malaysian study primarily focused on the association between fast-food consumption and overall academic performance, our regression analyses indicate that fast food significantly predicts lower GPA and OAPR but does not have a significant effect on the composite Academic Performance Index (API). The difference suggests the complex effects of eating habits on academic performance and increases the possibility that fast food consumption may have a stronger impact on grade-specific results rather than on more general measures of academic performance. Likewise, another study showed that university students who consumed more fast food had lower classroom performance (Asghar et al., 2023). This, along with other national data, highlights that while snack replacement and meal skipping were the best dietary predictors, eating fast food is still an important behavior that can worsen academic decline, particularly when done frequently alongside irregular meals.

Meal frequency or number of meals taken each day is another important behavioral aspect that influences academic performance. The frequency of meals consumed on daily basis was found to be a positive predictor across all the academic performance indicators including GPA, API, and OAPR. Students who ate the meals on daily basis performed better, highlighting the importance of meal regularity in students. Students who frequently ate 3 meals a day had greater academic performance than those who don't according to a study (Murakami et al., 2025). According to these findings, eating proper meals at regular basis enhances memory, learning and focus by boosting energy and nutrient supply. When investigating healthy dietary practices, a significant proportion of students reported inconsistent dairy intake and lower water intake, where fruit and vegetable intake was somehow better but still below the recommended levels. 54.7% of the students thought their dietary habits were average, while on the other hand only 28.9% thought they had good dietary habits. Overall, these findings add to the increasing amount of evidence showing that poor dietary habits are important factors that impact the academic performance of the student along with health. The results demonstrate that University of Management and

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Technology Lahore's female undergraduates are vulnerable to meal skipping, reliance on snacks and fast food, and have an unbalanced diet, which all together have a negative impact on academic performance. The most consistent negative predictors in overall multiple regression models were skipping meals and replacing them with snacks or fast food, while proper meal frequency demonstrated a protective effect.

This study has both academic and practical implications. The results are in line with global evidence that shows an association between diet and academic success. Proper meal consumption and better diet quality are consistently linked to better cognitive functions and academic grades, according to international studies conducted in the US, Europe, and Asia (Burrows et al., 2017). Very little research has been done on the correlation between diet and academic performance in university populations in Pakistan, and this study makes a contribution by giving context-specific findings. A better understanding of how the overall eating habits affect the performance of students is provided by this study, which includes a broader set of dietary indicators such as meal replacement, lunch and dinner skipping, fast food, fried food, snacks and sugary beverages, in contrast to many previous studies that mainly focused on breakfast consumption. This study comprehensively assessed various poor dietary habits at once using both the composite eating habits score and individual habit-specific analysis, in contrast to previous studies that mostly looked at individual dietary behavior separately. This allows a more detailed understanding of students' dietary habits. Women may have different eating issues, cultural issues and academic expectations than men, so it is very important that the study is gender-specific and solely focused on female undergraduate students. This holistic approach strengthens the finding's applicability.

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Incorporation of Chia Seeds as a Functional Ingredient in the Fortification of Apple Jam

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ABSTRACT

Jams are semi-solid food items made from seasonal fruits, but they often contain fewer nutrients as a result of thermal treatment. Nutraceuticals, like chia seeds, can help address this issue by fortifying jam with phytochemicals and tocopherols. This study aimed to make chia seed-fortified apple jam and assess its physical, chemical, and sensory properties as well as storage stability. Five different types of apple jam were developed, starting with the fundamental formulation (control), which contains no chia seeds. The other four jams included 5g, 10g, 15g, and 20g of chia seed. The protein content increased from 0.41% to 6.61%, while fiber content increased from 2.81% to 14.02%. Sensory evaluation of samples was done using a 9-point hedonic scale by a panel of 5 expert persons. The chia seed-fortified apple jam sample was dark, moderate red compared to the control sample's bright orange color. The results of this study proved that the addition of chia seeds does not have a significant influence on the value of pH. Chia seeds do not have a significant effect on °Brix and the titratable acidity value of jam. The values of titratable acidity and total phenolic content increased with the length of storage duration. Chia seeds help to lower bacterial load in the product. Chia seeds fortified apple jam exhibits good storage stability during 2 months of study. The findings suggest that apple jam fortified with chia exhibits good sensory qualities that can be used for jam production and other processed products to take advantage of the functional components in chia seeds.

Keywords: *Salvia hispanica*, Fortification, Apple, Malnutrition, Functional foods.

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INTRODUCTION

Jam is a semi-solid food product made from different fruits by cooking and containing sugar, pectin, and other ingredients. Jams are well known for their accessibility, affordability, and sensory qualities. They are typically canned and packed in clean vessels post-production (Muresan et al., 2014). Jams are processed to the appropriate consistency. Fruits often contain considerable pectin and acid content, which are extracted while processing, resulting in the production of the jam's textural attributes. Artificial pectin is added to the jam to reach the basic 1% pectin requirement, and external sources of acids are also added to meet the required pH. High-calorie jam has a total dissolved solids content of less than 50%, reduced-calorie jam has an entire dissolved solids content of up to 45%, and low-calorie jam should have a total dissolved solids content of more than 20% without the inclusion of sugar (Shinwari and Rao, 2018). After the fruits have been chopped and processed with various additives to the desired consistency, the jam is placed in sterile containers (Nduko et al., 2018). Jams often come in two varieties: the first is made from the puree of one fruit, whereas the other is made by combining the puree of two or maybe more fruits. Glucose slows the proliferation of microbes and keeps jams from spoiling. Sugar absorbs water, extending the storability of items (Nduko et al., 2018).

The most common tree fruit in the world, the apple, originated in Southwestern Asia. Apples (*Malus domestica*) are a significant source of phytochemicals and tocopherols (Brown, 2012). Apples contain 84.7% water and many phytonutrients and vitamins (Shah et al., 2015). Apples have the potential to prevent gastrointestinal malignancies, colorectal and hepatic malignancies, myocardial infarction, and breathing problems due to their diversified and quite well-constituted nature (Feliciano et al., 2010). Jams often contain less vitamin C because of the thermal treatment. Fortifying jam with nutraceuticals is one method for addressing this issue. Dietary supplementation can restore nutrients that were wasted through cooking or improve the wholesomeness of food by including micronutrients that are not already present in them (Naeem et al., 2017). Biofortification is an essential nutrition strategy to combat malnutrition and lower its prevalence in several low and moderate-income nations (Chadare et al., 2019).

Undernutrition, a severe health issue, is frequently caused by a lack of micronutrients, particularly in underdeveloped nations (Ramakrishnan et al., 2011). One of the most effective strategies to combat malnutrition caused by undernutrition is dietary supplementation (Bhagwat et al., 2014). As more individuals are becoming conscious of the dietary and physiological benefits of proteins, there is a massive rise in their need, particularly for the human diet. Plant proteins are popular due to their greater availability in nature, reduced production costs, and alignment with consumers' preferences based on nutritional requirements. In business, there is a growing interest in discovering proteins from alternative sources with superior functionalities. Because of their high abundance, digestibility, and favorable amino acid composition, seed proteins are gaining increasing attention (Timilsena et al., 2016). Beyond just providing basic nutritional needs, functional food ingredients offer physiological advantages and lower the risk of long-term illness (Ansari and Kumar, 2012). Chia seeds (*Salvia hispanica*) are just one of the foods with organic material. These seeds are uncooked, easy to consume, and contain the most significant amount of α-linolenic acid, up to 67.99% (Porras-Loaiza et al., 2014). Seeds have a higher protein content than other cereals, roughly 19–23% (Sandoval-Oliveros and Paredes-López, 2013). A suitable amount of essential amino acids is also present in chia seeds, including up to 42.2–42.9% of valine, leucine, and isoleucine. Seeds contain a greater percentage of essential amino acids than

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popular oil seeds like soy and sunflower. Non-essential amino acids like glutamic and aspartic acids are also abundant in chia seeds. Glutamic acid is thought to be an essential amino acid in food and improves sports performance (Olivos-Lugo et al., 2010). These also include significant levels of vitamins and minerals, as well as up to 41% of carbohydrates, 30% of fiber, 25% of proteins, and tocopherols that combat free radicals. These have no trans fatty acids or saturated fats (Timilsena et al., 2016).

Chia (*Salvia hispanica*) seeds are also used as a supplementary component in a variety of recipes made using packaged foods. The growing desire for better health and the rising prevalence of conditions, including overweight, type II diabetes, and CVD, are contributing to the rapid global growth of the chia seed (Coelho and de las Mercedes Salas-Mellado, 2015). It can also be used in jams, yogurt, fruit drinks, biscuits, and morning cereals (Attalla and El-Hussieny, 2017). Regular fruit jam is simple to spread and has a vivid color, pleasant fruit flavor, and a semi-solid texture, with no free fluid. It has uniform smoothness and no noticeable fruit fragments. Thus, fortification may alter the product's taste, flavor, physical appearance, and general acceptability by adding grit and bitterness. Fortification is delicate when a product's texture, like jam, must be maintained (Nduko et al., 2018). An appropriate balance of citric acid is necessary for making jam. Due to its higher citric acid content, lemon juice can be used in jam manufacturing as a substitute for citric acid (Ullah et al., 2018).

The objectives of this study were to develop chia seed fortified apple jam and to evaluate the nutritional and sensory properties of chia seed fortified apple jam. Chia seeds were added to apple jam as a fortifier, and their sensory qualities and desirability were assessed. Consequently, various chia seed proportions were combined to make apple jam. The prepared jam sensorial and proximate assessments showed that apple jam can be fortified with chia seeds.

MATERIALS AND METHODS

Material and reagents

Superior quality chia seeds were obtained from the local market of Faisalabad. Apples, sugar, and other required raw materials were also obtained from the local market of Faisalabad, Pakistan. Reagents were used for TPC, protein, fiber, and equipment used in different analyses obtained from the laboratories of the National Institute of Food Science and Technology, University of Agriculture, Faisalabad, Pakistan.

Preparation of chia seed fortified apple jam

Apple jam was prepared by the method described by Lee (Lee, 2014). Three independent jam batches were prepared for each treatment, and each analysis was performed in triplicate. For controlled jam, 1kg of sliced apples was taken, 100mL water, 10g of pectin, and 1kg of sugar were added, and pulp was cooked until the desired consistency was achieved. Citric acid and benzoic acid were added to the jam, and chia seeds were added for the other four treatments. Chia seeds were added in amounts of 5g, 10g, 15g, and 20g per 100g of the jam sample. Storage study done at the intervals of 0, 20, 40, and 60 days.

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Table 1: Treatment Plan of Apple Jam Fortified with Chia Seeds

Treatment	Jam Formulation	Chia Seeds (g/100g)
T0	100% Apple Jam	0
T1	95% Apple Jam + 5% Chia	5
T2	90% Apple Jam + 10% Chia	10
T3	85% Apple Jam + 15% Chia	15
T4	80% Apple Jam + 20% Chia	20

Quality analysis of chia seeds fortified apple jam

pH and Brix determination

Total soluble solids of apple jam were measured according to the method described by Ullah et al. (Ullah et al., 2018) using a digital refractometer. pH of the apple jam was measured using a pH meter following the standard method described by Kanwal et al. (Kanwal et al., 2017). The pH meter was calibrated with a buffer solution for precise results.

Determination of titratable acidity

Total titratable acidity of the jam was determined by the method described by Emelike and Akusu (Emelike and Akusu, 2019). The sample was homogenized, and phenolphthalein indicator was added and titrated against 0.1N NaOH until a light pink color appeared. The following formula was used to compute titratable acidity:

$$\text{Total Titratable acidity} = \frac{(V)(N \times \text{Meq.wt})}{\text{wt. of sample}} \times 100$$

Determination of moisture content

Moisture content of apple jam fortified with chia seeds was determined by using the hot air oven method (Bekele et al., 2020). Pre-dried china dishes were weighed, and a 5g sample of apple jam was heated for 24 hours in a hot air oven, then placed in a desiccator and allowed to cool to ambient temperature. Moisture content was calculated using the following formula:

$$\text{Moisture Content (\%)} = \frac{\text{Weight loss of sample (g)}}{\text{Sample weight (g)}} \times 100$$

Determination of protein content

Protein assay was determined by the method described by Bekele et al. (Bekele et al., 2020). Heat was applied to the digesting block until it reached the proper temperature. 0.1g of the sample was used to fill the digesting tubes with 5g of catalyst and 20mL of pure sulfuric acid. After an hour-long digesting process, the sample was given five to ten mins to cool, and 40mL of distilled water was put into a measuring cylinder. The process was distilled for 4 mins in a Kjeldahl tube containing 40mL of distilled water. A conical flask containing 60mL of boric

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acid solution was filled, and 2–3 drops of the indicator solution mixture were added. Sample tubes were positioned, and distillation continued until finished. 70mL of a 50% NaOH solution was then steam distilled for 4 mins. A blank run was performed with 40mL of distilled water. Samples were titrated with 0.1N HCl until the original hue was achieved, then 0.05 H_2SO_4 was needed to cause the color shift. A blank run was conducted to remove any N, allowing for the determination of the amount of acid solution needed. The following formula is used for calculation:

$$\%\text{Nitrogen} = \frac{\text{Normality of } H_2SO_4\,(0.1) \times (\text{mL acid for sample} - \text{blank}) \times 14 \times 100}{\text{Weight of sample} \times 1000}$$

$$\%\ \text{Crude protein} = \%\text{N} \times \text{conversion factor (6.25)}$$

Determination of fiber

The dietary fiber of apple jam fortified with chia seeds was determined by Naeem et al. (Naeem et al., 2017). A Megazyme kit was used to determine dietary fiber. Samples were heated at 100°C with heat-stable alpha amylase for 30–40 mins, and then incubated with protease and amyloglucosidase for hydrolysis. Ethanol was used to depolymerize and remove protein and glucose from starch. Residue was filtered and dried until constant weight. Dietary fiber was calculated by weighing the filtered residue and deducting the weight of protein and ash.

Total phenolic content (TPC)

The sample was prepared by dilution in 70% methanol and centrifuged for 10 mins at 3500 rpm and kept at 18°C. The Folin-Ciocalteau reagent was used to determine the total phenolic content of a sample using 0.5mL of jam, 2.5mL of Folin-Ciocalteau reagent, and 2mL of sodium carbonate solution. The absorbance at 765nm was estimated using a spectrophotometer, and gallic acid equivalents were calculated (Lafarga et al., 2018).

Total plate count

Microorganism growth is an essential factor in food spoilage, measured by plate count (Krishnaiya et al., 2016). The media nutrient agar was prepared by dissolving 7g in 250mL of distilled water, then sterilized in the hot air oven and cooled to 45°C. The four samples were diluted by pipetting, and 1mL of each sample was added to 9mL diluted water in a test tube. 20mL of cooled molten agar was placed into the Petri dish and gently swirled to distribute the inocula. After allowing the medium to harden, the plate was inverted and incubated at 30°C for 48 h. The results were then converted to CFU/g (colony-forming units per gram).

$$\text{CFU/g} = \frac{\text{No. of Colonies} \times \text{Dilution factors}}{\text{Volume of sample used}}$$

PAK. J. FOOD SCI., 30(1): 22-36
DOI: https://doi.org/10.65749/pjfs.2026.30.1.0004

Sensory evaluation

Sensory evaluation of samples was done using a 9-point hedonic scale by 50 expert persons from the National Institute of Food Science and Technology, University of Agriculture, Faisalabad, Pakistan. The parameters evaluated were color, flavor, aroma, texture, taste, spreadability, syneresis, and overall acceptability (Meilgard et al., 2016).

Statistical analysis

Minitab 18.1, a statistical program (two-way ANOVA), was used to analyze the raw data to determine the significant difference between the values (Montgomery, 2017).

RESULTS

Jam preparation

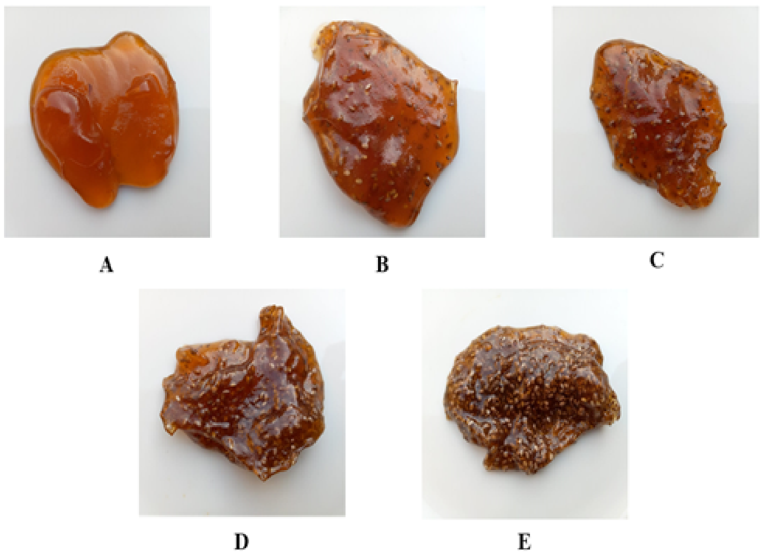

Figure 1: Pictures of chia seed fortified apple jam. A (control), B (5g), C (10g), D (15g), and E (20g) chia seeds

The pictorial images of apple jam created with apple fruit pulp, sugar, pectin, and chia seeds are shown in Fig. 1. The chia seed fortified apple jam sample is dark, moderate red compared to the control sample's bright orange color.

The results of total plate count (TPC), pH, titratable acidity, and total soluble solids (TSS) are presented in Table 2. According to statistical analysis, there were significant differences among all treatments ($p < 0.05$).

PAK. J. FOOD SCI., 30(1): 22-36
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Table 2: Physicochemical and microbial analysis of chia seed fortified apple jam

Trial	Amount of chia seeds (g)	Brix (°)	pH	Titratable acidity	TPC (log CFU/mL)
T0	0	67.82±0.18a	3.42±0.10b	0.53±0.02a	9.20±0.02a
T1	5	68.67±0.23a	3.16±0.05d	0.50±0.01a	6.63±0.02d
T2	10	67.88±0.30a	3.19±0.01cd	0.49±0.01a	6.40±0.01e
T3	15	67.88±0.31a	3.36±0.05bc	0.48±0.02a	7.12±0.02c
T4	20	68.54±0.83a	3.65±0.05a	0.49±0.04a	7.95±0.01b

Results are expressed as mean ± standard deviation of three replicates. Different superscript letters within a column indicate significant differences at $p < 0.05$.

pH and Brix

The jam samples fortified with chia seeds ranged in pH from 3.16 to 3.65 compared to the sample without any chia seeds (control), which had a pH of 3.42. Among all the treatments, T1 showed lower pH values, which were 3.16 (Table 2). The chia seed-fortified sample had a Brix value of 68.67–68.54° compared to the control sample's Brix of 67.82°. Among all the treatments, T0 showed lower values of °Brix, which was 67.82° (Table 2). There were no significant changes in the °Brix during the storage study of 2 months, but the pH value decreased during the storage period. The lowest value of pH recorded for jam was 3.11 for T2 at day 60.

Titratable acidity

The jam samples fortified with chia seeds ranged in titratable acidity from 0.49 to 0.50 compared to those without chia seeds (control), which had titratable acidity of 0.53. Among all the treatments, T3 showed lower titratable acidity values, which were 0.48 (Table 2). Titratable acidity increased with the storage period. The highest value of titratable acidity recorded for jam was 0.56 for T4 at day 60.

Total plate count

As measured by plate count, microorganism proliferation significantly contributed to food spoilage. The jam samples without chia seeds have a TPC of 9.20 (log CFU/mL), while samples fortified with chia seeds ranged in TPC from 6.63 to 7.95 (log CFU/mL). Among all the treatments, T2 showed lower values of TPC (bacterial count), which was 6.40 (log CFU/mL) (Table 2). TPC of jams increases with the length of storage period; the highest value of TPC recorded for jam was 8.99 (log CFU/mL) for T0 at day 60.

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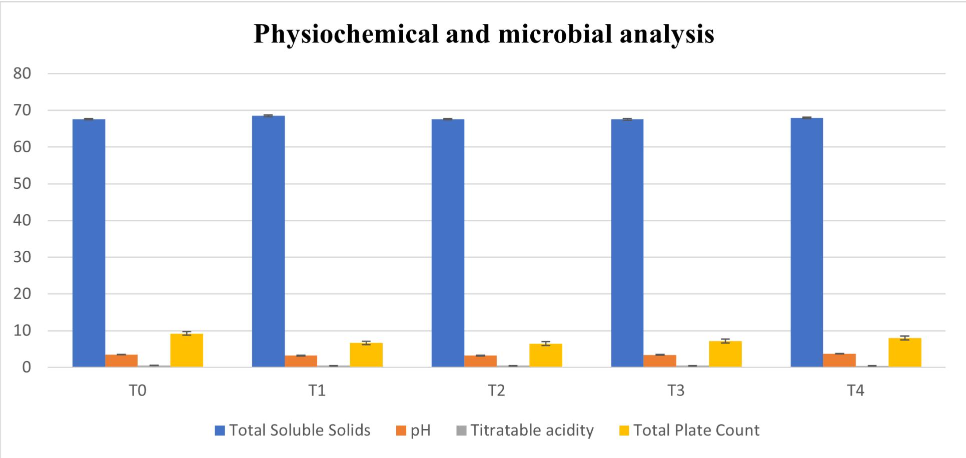

Figure 2: Physicochemical and microbial analysis of chia seed fortified apple jam

Protein

Apple jam (control) had a total protein content of 0.41%, while the protein content of the other four jams fortified with chia seeds ranged from 1.61% to 6.61%, depending on how many chia seeds were used. One-way ANOVA was used to determine how the protein content varied. Tukey's HSD test revealed that the protein concentration of each jam composition varied significantly (Table 3).

Table 3: Proximate and antioxidant analysis of chia seed fortified apple jam

Trial	Amount of chia seeds (g)	Protein (%)	Fiber (%)	Moisture (%)	TPC (mg GAE/L)
A	0	0.41±0.01e	2.81±0.01e	30.48±0.00a	120.72±0.34e
B	5	1.61±0.01d	4.01±0.01d	29.51±0.01b	172.70±0.25d
C	10	3.72±0.02c	6.24±0.01c	29.48±0.00c	211.90±0.06c
D	15	5.04±0.01b	9.52±0.01b	28.75±0.01d	219.50±0.49b
E	20	6.61±0.01a	14.02±0.02a	28.68±0.00e	282.61±0.41a

Results are expressed as mean ± standard deviation of three replicates. Different superscript letters within a column indicate significant differences at $p < 0.05$.

Fiber

The jams that had chia seeds-fortified jams had a higher fiber content overall. Apple jam (control) had a total fiber content of 2.81%, while the fiber content of the other four jams fortified with chia seeds ranged from 4.01% to 14.02%. One-way ANOVA was used to determine how the fiber content varied. Tukey's HSD test revealed that the fiber concentration of each jam composition varied significantly (Table 3).

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Moisture

The jam samples fortified with chia seeds ranged in moisture content from 29.51% to 28.68% compared to the sample without any chia seeds (control), which had a moisture content of 30.48%. Among all the treatments, T4 showed lower values of moisture percentage, which was 28.68% (Table 3).

Total phenolic content

In comparison to the jam sample without any chia seeds (control), which had a total phenolic content of 120.72 mg GAE/L, the jam samples fortified with chia seeds ranged in total phenolic content from 172.70 to 282.61 mg GAE/L. T4 outperformed the other treatments in terms of total phenolic content, with a value of 282.61 mg GAE/L (Table 3). Total phenolic content of jams increased with the length of storage period; the highest value of TPC recorded for jam was 283 mg GAE/L for T4 at day 60.

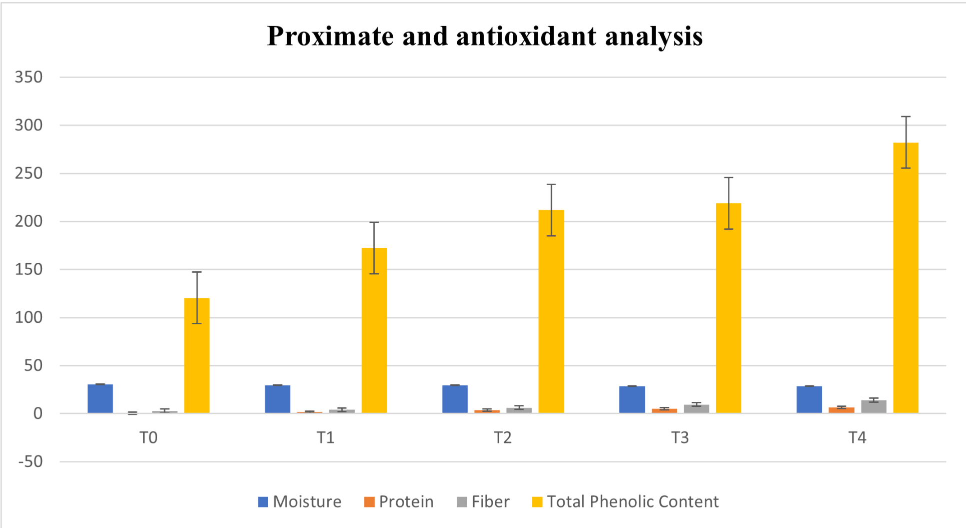

Figure 3: Proximate and antioxidant analysis of chia seed fortified apple jam

Sensory analysis

Table 4 demonstrates how adding chia seeds significantly altered the sensory qualities assessed by the tasting panel. The addition of 10g of chia seeds did not dramatically modify the color or texture of the jam, according to the results, but adding more chia seeds led to noticeable modifications. On the other hand, adding chia seeds to the jam had a minimal impact on the spreadability of the jam but had a significant effect on the flavor and general acceptance of the jam. The sensory quality of the jam was negatively impacted by adding chia seeds at rates of 15g and 20g per 100g of the jam sample. T2, however, showed promising outcomes in terms of overall acceptability.

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Table 4: Sensory analysis of chia seed fortified apple jam

Attributes/Trials	A	B	C	D	E
Aroma	7.62±0.01b	7.63±0.02b	8.10±0.10a	7.57±0.21b	6.83±0.03c
Flavor	8.20±0.00b	7.83±0.05c	8.61±0.01a	6.24±0.05d	5.26±0.05e
Color	8.23±0.03b	8.25±0.05b	8.83±0.03a	6.42±0.04c	6.13±0.15d
Taste	8.20±0.00b	8.20±0.00b	8.61±0.01a	6.24±0.05c	5.81±0.01d
Texture	8.23±0.03b	8.25±0.05b	8.42±0.02a	6.03±0.06c	4.81±0.02d
Spreadability	8.03±0.05b	8.10±0.17ab	8.33±0.30a	6.83±0.05c	5.28±0.07d
Syneresis	8.25±0.05c	8.42±0.02b	8.98±0.03a	7.06±0.05d	8.25±0.05c
Overall acceptability	8.03±0.05c	8.42±0.02b	8.83±0.03a	6.03±0.06d	4.24±0.05e

Sensory scores are presented as mean ± SD. Different superscript letters within a row indicate significant differences at $p < 0.05$. Trials A, B, C, D, and E represent control, 5g, 10g, 15g, and 20g chia seeds added per 100g of jam sample, respectively.

DISCUSSION

Jams are widely consumed due to their low cost, year-round availability, and organoleptic qualities, and various fruits are utilized in their production (Baker et al., 2005). According to the spreadability ratings of the formed jams, the chia seed inclusion did not affect how the jam gelled. The protein content of the control jam was 0.41%, comparable to the displayed protein content of 0.06% (Ahmmed et al., 2015). The protein content of apple jam is low because common ingredients used in the production of jam are not a good source of protein, including pectin, sugar, fruits, benzoic acid, and citric acid. The inclusion of chia seeds in apple jam increases the protein content. Chia seeds are a good source of protein (16.5%), and their protein value is higher than most cereal group foods (Valdivia-López and Tecante, 2015). Chia seeds are a worthy source of essential and non-essential fatty acids (Kulczyński et al., 2019). Chia seeds can be used to fortify low-protein foods like apple jam. One more valuable component of chia seeds is their high fiber content, and they also contain many bioactive components, making them a superfood. The addition of chia seeds to apple jam also increased the jam's fiber content. Chia seeds include both insoluble fibers, which make up the majority of the diet, and soluble dietary fiber, which is fermented in the colon (Anderson et al., 2009). Dietary fiber facilitates efficient digestion, which facilitates bowel movement and has numerous positive health effects (Satija and Hu, 2012). The incorporation of chia seeds in apple jam endows it with advantageous functional ingredients since the presence of the essential fatty acids, particularly α-linolenic acid (Marcinek and Krejpcio, 2017). The results of this study have proved that the addition of chia seeds does not have a significant influence on the value of pH. The pH is an important factor in the gel formation of jam. Like pH, chia seed do not significantly affect the °Brix and titratable acidity value of jam. The values of pH decreased with the increase of storage period while the values of titratable acidity increased. Chia seeds are a good source of antioxidants, which is why they help to lower bacterial load in the product. The values of total plate count and total phenolic content increased with the increase of storage period. Color and texture are important sensory qualities that influence consumer approval. Chia seed additions of 5g and 10g did not appreciably change the product's color or texture, proving that higher chia seed dosages could not be tolerated.

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The use of whole chia seeds may have contributed to the low scores for the texture where chia seeds were used in higher concentrations. Although chia seeds have a mild flavor, they do not have significant impact on the jam's flavor. This might be explained by perception as a result of the jam's new ingredient, which consumers might not be familiar with. Spreadability was unaffected, which may have been because chia seeds formed a viscous solution. Chia seed have gel-forming ability which is beneficial in the development of perfect jam (Segura-Campos et al., 2014). General acceptability indicated that T2 was the most preferred chia seed-fortified jam. Apple jam fortified with low levels of chia seeds gains acceptability from consumers while jams containing higher concentration of chia seeds was not acceptable. Chia seeds fortified apple jam exhibit good storage stability during 2 months of study. Chia seed product development is highly desirable in the food industry and has the potential to be used in nutraceutical food items.

Adding chia seeds improved nutritional content; however, higher inclusion levels reduced texture acceptability, while 10 g/100 g remained acceptable (protein increased from 0.41% to 6.61%, and fiber enhanced from 2.81% to 14.02%). Consumers were less prepared to trade the sensory qualities of apple jams for the functional qualities and health advantages of chia seeds, even though chia seeds have been accepted for their functional qualities. At the outset of the product development process, this fact needs to be considered. However, adding chia seeds in smaller amounts (such as 10g) seemed to have little impact on the sensory qualities and to be better tolerated, suggesting that formula optimization is crucial for product development and raising consumer awareness of the health advantages of functional products.

Competing Interests

The authors declare that they have no competing interests.

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Author's contribution

Anam Matloob conducted the experiments and investigation and wrote the original draft. Muhammad Atif Randhawa conceptualized, supervised the research work, and proofread the manuscript. Hafiz Muhammad Jawad Saleem helped in writing this manuscript, used statistical software, and proofread the manuscript.

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Development and Characterization of Papaya Enriched Snack Bars for Diabetes Management

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ABSTRACT

The incidence of diabetes has been increased significantly in recent years attributed to sedentary lifestyle and associated behavioral factors. However, this condition can be effectively managed through targeted modifications in lifestyle and dietary patterns. In response to increased consumer demand for healthier snack foods, this study focused on development and characterization of papaya enriched snack bars providing both energy and functional bioactives simultaneously. Papaya pulp powder and papaya leaf powder were added in different concentrations to formulate papaya-based energy bars (T0–T3). Roasted chickpea powder, apricot paste, and date paste were used as base ingredients. The papaya pulp, papaya leaf and the developed papaya-based bars were evaluated for proximate composition, antioxidant potential, sensory qualities. The bars were also tested for in vitro inhibitory activity of α-glucosidase, α-amylase for the evaluation of antidiabetic potential. The findings indicated a significant difference in the proximate composition, antioxidant and antidiabetic potential of the bars. The bars with added papaya pulp and papaya leaf (T1–T3) had higher levels of ash and crude fiber and better antioxidant activity as compared to the control (T0). Amongst bars, T3 showed the highest antioxidant potential determined by DPPH and FRAP assay. The enzymes inhibition activity of bars revealed that T3 was more effective in inhibiting both α-glucosidase and α-amylase indicating the strongest antidiabetic potential. Conclusively, the addition of papaya pulp and leaf powder improved the functional and nutritional properties of chickpea-based bars, without affecting the sensory attributes, indicating their suitability in development of functional snacks.

Keywords: Papaya pulp powder; Papaya leaf powder; Hypoglycemic activity; Antioxidant potential; Functional snacks

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INTRODUCTION

Over the recent years, scientific research uncovering the underlying cause of diabetes mellitus has thrived considerably, led by the ultimate development of treatment strategies and effective prevention. Diabetes Mellitus (DM), a group of metabolic disorders is characterized by hyperglycemia, resulting either from decreased or impaired insulin production or action. Diabetes mellitus with chronic hyperglycemia damages vital organs, including the retina of the eye, heart and nervous system, the kidney, and the blood vessels (Alam et al., 2022). Multiple environmental factors are implicated in the onset of DM, including obesity, inflammation, physical inactivity, and genetic predisposition. Globally, DM shows an increasing health crisis, with a high prevalence rate in Asian, African, and Eastern Mediterranean regions (Saeedi et al., 2019). The International Diabetes Federation (IDF) reports that in 2024, about 11.1% of adults aged 20–79 years were living with diabetes worldwide, which is roughly 589 million people. This number is expected to increase further, reaching around 12.9% or 853 million individuals by 2050. The rising prevalence is mainly linked to factors such as urbanization, aging populations, physical inactivity, and increasing obesity rates, with the greatest burden observed in low- and middle-income countries (Genitsaridi et al., 2026).

Diabetes Mellitus has been strongly associated with oxidative stress, characterized by excessive production of reactive oxygen species resultant to chronic hyperglycemia. This ultimately affects glucose metabolism, triggering chronic inflammation leading to impairment of pancreatic β-cells. Pharmacological intervention and lifestyle changes along with antioxidant rich diet has shown the potential to lower oxidative damage and prevent vascular and heart problems in type 2 diabetes mellitus (T2DM). In this context, plant foods with antioxidant and antihyperglycemic properties are being considered as complementary therapies (Ansari et al., 2023).

Low- and very-low-carbohydrate diets have been widely evaluated for glycemic control and the management of T2DM, and have been associated with significant reduction in HbA1c levels, particularly emphasizing minimally processed foods (Goldenberg et al., 2021). Dietary strategies focusing on intake of phytonutrient dense foods with low-glycemic index offer metabolic advantages and may play significant role in the management of T2DM (Qiang et al., 2025). Low glycemic index diets manage postprandial glucose drive and lower insulin demand and have been indicated to improve fasting glucose and HbA1c (Peres et al., 2023). Moreover, plant components high in polyphenols have antioxidant activity and facilitate regulation of glucose signaling pathways, lower oxidative stress, which is a major risk factor in diabetes and associated complications (Martiniakova et al., 2025).

Among such plants, papaya has gained scientific attention for its potential to lower blood glucose levels due to its high content of fiber, vitamin C, saponins, and flavonoids and offer practical benefits because of its affordability, nutrient density, and availability (Zuhria Ismawanti et al., 2019). Papaya leaf extracts are promising functional components in glycemic management. Owing to their rich phytochemical profile, including polyphenols, flavonoids, and alkaloids papaya leaves can inhibit key carbohydrate-digesting enzymes α-amylase and α-glucosidase, increase insulin signaling, and decrease oxidative stress (Nyakundi et al., 2024).

Papaya leaves are rich in phenolics, flavonoids, alkaloids, and carotenoids, bioactive compounds showing potent antioxidant and anti-inflammatory effects have been associated with multiple antidiabetic mechanisms. A significant number of studies have illustrated modulation of glucose metabolism, enzyme inhibition, and lipid profile improvement across in-vitro and animal study

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models (Sharma et al., 2022; Nyakundi et al., 2024). Papaya leaf phytochemistry analysis revealed the presence of ferulic acid, saponins and quercetin compounds. These compounds have shown strong antioxidant and anti-inflammatory activity in α-amylase and α-glucosidase inhibition assays in-vitro (Chaijan et al., 2024).

Research studies demonstrated the potential of papaya leaf extracts in suppressing carbohydrate metabolizing enzymes, thereby, reducing postprandial blood glucose. The papaya leaf extracted in methanol showed elevated α-glucosidase inhibition activity. This leaf fraction focused on a direct mechanistic pathway for glycemic control. An in vivo study for the evaluation of antidiabetic effect of papaya leaf extract highlighted that methanolic papaya leaf extract inhibited the α-glucosidase activity in rats (Abubakar et al., 2019). These findings highlighted the beneficial role of papaya leaf in making different snack bars or functional products, which will help manage T2DM. Despite of bitter taste of papaya leaf, it has exceptional therapeutic use positively impacting plasma insulin, low density lipoproteins and triglycerides (Sobia et al., 2016). *Carica papaya* contains various chemical compounds, such as caffeic acid, myricetin, rutin, quercetin, α-tocopherol, papain, and kaempferol, exhibit significant antioxidant properties (Kong et al., 2021). These compounds are found in different parts of the papaya plant, including the pulp, leaves, and seeds, possess notable antioxidant properties, along with antihypertensive, hypoglycemic, and hypolipidemic effects (Santana et al., 2019).

The increasing global prevalence of T2DM, the role of dietary management in glucose regulation and growing consumer demand for functional products emphasized the urgent need for the development of functional snack bars. Papaya pulp and papaya leaves, with their rich phytochemical profile, combined with other low-glycemic, antioxidant-rich ingredients such as chickpea powder, dried apricot paste, and dates, can be a promising strategy for functional snack formulations. In this context this study aimed to formulate papaya enriched snack bars by incorporating papaya pulp and papaya leaf into chickpea, apricot and date-based bars. Additionally, the study aimed to assess the nutritional composition, antioxidant properties and antidiabetic potential of the formulated bars. This research intends to provide an affordable and functional food-based strategy for glucose regulation in diabetes mellitus management.

MATERIALS AND METHODS

Procurement of Materials

Papaya pulp, papaya leaves roasted chickpeas, dates, and dried apricots were procured from local organic source. Analytical grade chemicals were used to evaluate the proximate composition, antioxidant and antidiabetic potential.

Development of Papaya-Enriched Bars

Four formulations of snack bars were developed to study the effect of incorporation of papaya pulp and papaya leaf powder on the nutritional, antioxidant and antidiabetic potential of the bars (Table 1). Chickpeas were grinded to powder using an electric grinder, and combined with apricots paste and date paste.

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Table 1: Formulations of papaya pulp and leaf-based bars

Ingredients	T0	T1	T2	T3
Chickpea Powder (g)	3.5	3.2	2.95	2.7
Papaya Pulp Powder (g)	0	0.25	0.5	0.75
Papaya Leaf Powder (g)	0	0.05	0.05	0.05
Apricot Paste (g)	3	3	3	3
Date Paste (g)	3.5	3.5	3.5	3.5
Total weight (g)	10	10	10	10

Nutritional Evaluation

The proximate composition of papaya pulp powder, papaya leaf powder and the papaya-based snack bars including the ash content, moisture content, crude fat, crude protein, and crude fiber were evaluated according to AACC (2000). The nitrogen-free extract (NFE) was calculated by method of difference.

Extract Preparation

Ethanolic extracts were prepared by weighing 10 g of powdered sample into a centrifuge tube and adding 100 mL of Ethanol. The mixture was sonicated for 20 minutes in an ultrasonic bath to improve the extraction of bioactive compounds, progressing into centrifugation at 3000 rpm for 10 minutes. The supernatant was carefully collected and used as the working extract for phytochemical and antioxidant assays. All extractions and analyses were performed in triplicates.

Analysis of Antioxidants

The antioxidant capacity of papaya-based bars was evaluated using the DPPH radicle scavenging assay and Ferric Reducing Antioxidant Power (FRAP) assay. DPPH activity was determined following the method described by Brand-Williams et al. (Brand-Williams et al., 1995). Briefly, 2 mL of sample was mixed with 2 mL of 0.1 mM DPPH solution in ethanol and incubated in the dark at room temperature for 30 mins. The absorbance was measured at 517 nm using a spectrophotometer. The FRAP assay was performed according to Benzie and Strain (Benzie and Strain, 1996). A 40 μL aliquot of sample extract was mixed with 1.8 mL of FRAP reagent, consisting of 10 mM TPTZ in 40 mM HCl, 20 mM $FeCl_3$ and 0.3 M acetate buffer (pH 3.6). The mixture was incubated and absorbance was recorded at 595 nm using Trolox as standard.

Phytochemical Analysis

The phytochemical analyses of all the bars were performed in triplicates (Usman et al., 2009). The phenol content of bars was analyzed by using Folin Ciocalteu method. 0.5 mL of extract and 2.5 mL of Folin reagent were mixed in a test tube. After 5 minutes, 2.5 mL of sodium carbonate was added. Then, test tubes were incubated in dark for 45 minutes. After incubation, absorbance was measured by using spectrophotometer at 765 nm. Gallic acid was used as a standard. The total flavonoid content was measured by using aluminum chloride colorimetric method. A 500 μL sample extract was added to 2 mL of water and 150 μL of 5% $NaNO_2$ and the solution was

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kept at room temperature for 6 mins. Afterward, 150 μL of 10% of $AlCl_3$ was added then again incubated for 6 mins. This was followed by the addition of 2 mL of 4% NaOH. Immediately absorbance was measured at 450 nm. Quercetin was used as a standard.

Analysis of Enzyme Inhibition Assays

The anti-diabetic potential of papaya pulp powder and papaya leaf powder snacks bars were assessed using enzyme assays including α-amylase inhibition assay and α-glucosidase inhibition assay. For α-amylase inhibition assay, 100 μL of sample was added in the solution of 0.1 M phosphate buffer (pH 6.8 was maintained) and α-amylase enzyme and incubated for 10 minutes at room temperature. After incubation DNSA reagent was added and the mixture was boiled for 5 minutes to stop the reaction and the absorbance was measured at 540 nm. For α-glucosidase inhibition assay, 100 μL of sample was added in the solution of 0.1 M phosphate buffer maintained at pH 6.9 followed by addition of 50 μL α-glucosidase enzyme. The mixture was incubated for 20 mins at room temperature. Afterwards, 10 mM of PNPG substrate was added and again incubated at 37 °C for 30 mins. Afterwards, 1 M sodium carbonate was added to stop the reaction and absorbance was measured at 405 nm.

Physical Analysis

The physical properties of bars including color and texture were analyzed by using the standard method of AACC (2000). Texture analysis included the measurement of hardness, springiness and cohesiveness of bars by using a textural analyzer. A digital colorimeter was used for the for measurement of L^* value indicating lightness, a^* value indicating positive red and negative green, b^* value indicating positive yellow and negative blue.

Sensory Evaluation

The sensory evaluation of all formulations was carried out using a 9-point hedonic scale by a panel of 20 semi-trained individuals including students from different departments and teachers. The parameters assessed include texture, appearance, mouthfeel, taste, aroma, aftertaste, and overall acceptability.

Statistical Analysis

All the data collected in triplicates was subjected to statistical analysis. Descriptive statistics with mean and standard deviations and one way ANOVA was carried out using IBM SPSS statistics 25 at confidence level of 95%. For post-hoc test, LSD was used to scrutinize the intra group variations.

RESULTS

Proximate Analysis of Papaya Pulp and Leaf Powder

The proximate composition of papaya leaf and pulp powder was analyzed to evaluate the nutritional profile (Figure 1). The outcomes showed that the moisture content of papaya pulp are slightly higher than papaya leaf powder 1.07% and 1.02% respectively. The ash content of

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papaya pulp powder was higher than papaya leaf powder. The proximate analysis of bars (Table 2) revealed a statistically significant difference in moisture, ash, crude protein, crude fat, crude fiber, and nitrogen-free extract due to enrichment with papaya pulp and papaya powder. The moisture content ranged from 38% in T0 to 39% in T1 with a slight variation across treatments. Crude protein content was highest in the control bar (T0: 5.62%) and decreased slightly but significantly in papaya-enriched formulations (T1: 5.32%, T2: 5.33%, T3: 5.41%), which is due to substituting a portion of chickpea powder the primary protein source in the formulation with papaya pulp powder. Crude fat content increased progressively from T0 (1.40%) to T3 (1.63%). The crude fat content across all formulations remained low, which is advantageous from a diabetes management perspective, as low-fat functional foods are preferred in the dietary management of cardiometabolic risk associated with T2DM. Crude fiber content was significantly higher in T1 and T2 (1.41% each) compared to T0 (1.02%) and T3 (1.38%). Ash content was highest in T0 (3.65%) and declined in papaya-enriched bars, likely reflecting the higher mineral density of roasted chickpea powder relative to papaya pulp powder. The proximate composition of papaya leaf powder exhibited considerably higher ash (16.3%), protein (14.27%), and fiber (16.50%) compared to papaya pulp powder, confirming that leaf powder is nutritionally denser.

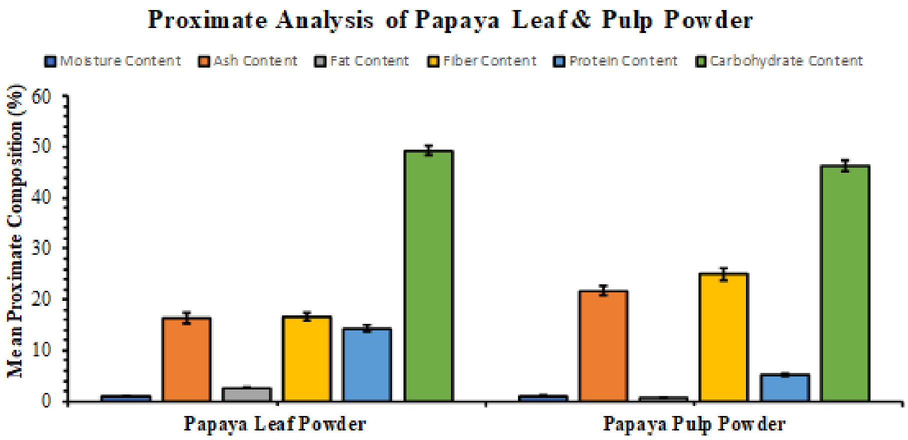

Figure 1: Proximate Analysis of Papaya Leaf and Pulp powder along with the variations

Table 2: Proximate composition of papaya pulp and leaf-based bars

Treatment	Moisture (%)	Ash (%)	Protein (%)	Fat (%)	Fiber (%)	Carbohydrate (%)
T0	38.75±0.07c	3.65±0.02a	5.62±0.03a	1.40±0.01d	1.02±0.03c	48.26±0.04c
T1	39.23±0.09b	2.33±0.01d	5.32±0.02d	1.52±0.10c	1.41±0.01a	50.19±0.15b
T2	39.80±0.17a	2.65±0.01c	5.33±0.02c	1.56±0.09b	1.41±0.02a	48.11±0.11d
T3	38.52±0.15d	2.66±0.01b	5.41±0.03b	1.63±0.02a	1.38±0.02b	50.40±0.18a

Values are represented as mean ± SD (n = 10). Means with different letters varied significantly. T0 = 0% papaya pulp and leaf powder, T1 = 2.5% papaya pulp powder, T2 = 5% papaya pulp powder, T3 = 7.5% papaya pulp powder. All the formulations have same 0.5% papaya leaf powder content.

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Antioxidant Activity

The antioxidant potential and phytochemical composition of papaya pulp & leaf powder (Table 3) and papaya-based snack bars (Table 4) assessed through DPPH radical scavenging activity, ferric reducing antioxidant power (FRAP), total phenolic content (TPC), and total flavonoid content (TFC), demonstrated a clear and progressive enhancement with increasing papaya ingredient incorporation. The DPPH radical scavenging activity increased significantly from 40.80% in T0 to 79.98% in T3, while FRAP values rose from 0.64 to 0.96 μmol TE/g across the same range. TPC and TFC followed parallel dose-dependent trends, with T3 recording the highest values of 1.56 mg GAE/g and 70.21 mg QE/g, respectively, compared to T0 (1.25 mg GAE/g; 35.63 mg QE/g). Antioxidant activity was much higher in treatments that contained papaya powder and papaya leaf powder than in the control group. The polyphenolic and flavonoid chemicals found naturally in papaya leaf and pulp were directly responsible for this enhancement, as they enhanced the bars' capacity to scavenge radicals.

Table 3: Antioxidant properties of papaya pulp and leaf powder

Powders	TPC (mg GAE/g)	TFC (mg QE/g)	DPPH (% inhibition)	FRAP (μmol TE/g)
PLP	1.97±0.01	271.7±0.00	84.70±0.04	3.47±0.01
PPP	1.89±0.01	268.56±0.00	86.44±0.14	3.40±0.02

Values are represented as mean ± SD (n = 10). Means with different letters varied significantly. PLP = papaya leaf powder; PPP = papaya pulp powder

Table 4: Antioxidant properties of papaya pulp and leaf-based bars

Treatments	TPC (mg GAE/g)	TFC (mg QE/g)	DPPH (% inhibition)	FRAP (μmol TE/g)
T0	1.25±0.00d	35.63±0.01d	40.80±0.03d	0.64±0.06d
T1	1.39±0.00c	57.55±0.00c	58.09±0.11c	0.65±0.01c
T2	1.47±0.00b	60.71±0.01b	75.50±0.03b	0.83±0.01b
T3	1.56±0.03a	70.21±0.00a	79.98±0.01a	0.96±0.00a

Values are represented as mean ± SD (n = 10). Means with different letters varied significantly. T0 = 0% papaya pulp and leaf powder, T1 = 2.5% papaya pulp powder, T2 = 5% papaya pulp powder, T3 = 7.5% papaya pulp powder. All the formulations have same 0.5% papaya leaf powder content.

Enzyme Inhibition Assay

α-Amylase Inhibition Assay

Among powders, papaya leaf powder has shown (Table 5) a potent increase in α-Amylase inhibition activity of bars (70.2%) as compared to papaya pulp powder which has shown a mild inhibition in enzyme activity (18.7%). The papaya enriched snack bars (Table 6) have shown mild to moderate increase in inhibition percentage by reducing starch digestion. The mild to moderate trend was due to the less amount of papaya leaf powder in the bars. The findings of α-amylase inhibition activity illustrated the remarkable difference between T0 and other

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treatment groups. T0 with no addition of papaya pulp and papaya leaf has the lowest enzyme inhibition activity among all snack bars.

Table 5: α-Amylase Inhibition Assay of papaya pulp and leaf powders

Powders	**Mean Absorbance**	**% Inhibition**
PLP	0.41 ± 0.01	70.2 ± 1.5
PPP	0.86 ± 0.02	18.7 ± 0.7

Values are represented as mean ± SD (n = 10). Means with different letters varied significantly. PLP = papaya leaf powder; PPP = papaya pulp powder

Table 6: α-Amylase Inhibition Assay of papaya pulp and leaf-based bars

Treatments	**Mean Absorbance**	**% Inhibition**
T0	0.93 ± 0.02	10.2 ± 0.5d
T1	0.81 ± 0.01	22.4 ± 0.8c
T2	0.77 ± 0.02	27.3 ± 0.9b
T3	0.74 ± 0.01	30.1 ± 1.0a

Values are represented as mean ± SD (n = 10). Means with different letters varied significantly. T0 = 0% papaya pulp and leaf powder, T1 = 2.5% papaya pulp powder, T2 = 5% papaya pulp powder, T3 = 7.5% papaya pulp powder. All the formulations have same 0.5% papaya leaf powder content.

α-Glucosidase Inhibition Assay

The findings of α-glucosidase inhibition assay of papaya pulp & leaf powders, and papaya-based bars, have been represented in Table 7 and 8, respectively. The enzyme inhibition results of individual powders revealed that leaf powder has 70.2% α-amylase inhibition and 78.1% α-glucosidase inhibition, substantially greater than pulp powder (18.7% and 24.8%, respectively). The results demonstrated a consistent and significant dose-dependent increase in inhibitory activity across both enzyme assays as the proportion of papaya pulp powder increased from T0 to T3. For α-amylase inhibition, values increased from 10.2% in T0 to 30.1% in T3, while α-glucosidase inhibition progressed from 12.1% in T0 to 37.0% in T3. The impact of papaya pulp powder is more prominent in α-glucosidase assay. All the snack bars showed almost same trend as of alpha amylase. T0 bar showed lowest α-glucosidase inhibition value. The bars supplemented with papaya leaf powder and papaya pulp powder indicated gradually increased inhibition values. Inhibition values progressively increased from T1 (28.3%) to T3 (37%).

Table 7: α-Glucosidase Inhibition Assay of papaya pulp and leaf powders

Powders	**Mean Absorbance**	**% Inhibition**
PLP	0.39 ± 0.01	78.1 ± 1.4
PPP	0.90 ± 0.02	24.8 ± 0.8

Values are represented as mean ± SD (n = 10). Means with different letters varied significantly. PLP = papaya leaf powder; PPP = papaya pulp powder

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Table 8: α-Glucosidase Inhibition Assay of papaya pulp and leaf-based bars

Treatments	**Mean Absorbance**	**% Inhibition**
T0	1.00 ± 0.02	12.1 ± 0.6d
T1	0.88 ± 0.02	28.3 ± 1.0c
T2	0.84 ± 0.01	33.5 ± 1.1b
T3	0.80 ± 0.02	37.0 ± 1.2a

Values are represented as mean ± SD (n = 10). Means with different letters varied significantly. T0 = 0% papaya pulp and leaf powder, T1 = 2.5% papaya pulp powder, T2 = 5% papaya pulp powder, T3 = 7.5% papaya pulp powder. All the formulations have same 0.5% papaya leaf powder content.

Physical Characteristics

The findings of physical parameters including texture and color of papaya-based bars have been shown in Table 9 and 10. All the sample bars showed almost same hardness level. The addition of papaya pulp or leaf powder did not significantly alter the bars hardness. Texture analysis (Table 9) revealed that hardness values were remarkably consistent across all formulations (approximately 3.19–3.20 $\times$ 10^5 units), indicating that the progressive substitution of chickpea powder with papaya pulp powder at levels up to 7.5% did not significantly alter the structural integrity of the bars. This is a favorable finding, as hardness is a critical quality attribute for snack bars, affecting consumer perception, ease of consumption, and product shelf stability. The inclusion of 0.5% PLP across all treatment bars may have contributed a minor structural reinforcement effect due to its fiber content, though the concentration was too low to produce statistically discernible differences in hardness.

Cohesiveness and adhesiveness showed more notable variation, with T0 exhibiting the highest cohesiveness (12.7 $\times$ 10^2), which declined substantially in T1 and T2 before partially recovering in T3 (6.37 $\times$ 10^2). This pattern suggests that the interaction between papaya pulp powder and the date-apricot paste matrix alters the internal binding forces within the bar structure. Adhesiveness was highest in T3 (3.44 $\times$ 10^2), potentially reflecting the increased moisture-retaining properties of papaya pulp at higher inclusion levels, which can enhance surface stickiness. These textural differences, while statistically significant, fall within a range that would not substantially compromise the mechanical performance of the bars as consumer products. Color analysis (Table 10) demonstrated a systematic and progressive decrease in lightness (L^*) from T0 (27.97) to T3 (19.63), alongside reductions in both the redness (a^*) and yellowness (b^*) values. The shift in a^* values from positive (reddish, T0: 5.50) to lower positive values in treated bars reflects the masking of the reddish-brown tones of date and apricot paste by the greenish contribution of leaf powder.

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Table 9: Texture analysis of formulations

Treatments	Hardness ($\times 10^5$)	Cohesiveness ($\times 10^2$)	Adhesiveness ($\times 10^2$)
T0	3.19 ± 0.01	12.7 ± 0.4	2.27 ± 0.1
T1	3.19 ± 0.02	3.18 ± 0.2	1.74 ± 0.1
T2	3.19 ± 0.01	3.18 ± 0.1	1.73 ± 0.1
T3	3.20 ± 0.02	6.37 ± 0.3	3.44 ± 0.2

Values are represented as mean ± SD (n = 10). Means with different letters varied significantly. T0 = 0% papaya pulp and leaf powder, T1 = 2.5% papaya pulp powder, T2 = 5% papaya pulp powder, T3 = 7.5% papaya pulp powder. All the formulations have same 0.5% papaya leaf powder content.

Table 10: Color analysis of formulations

Treatments	L^* (lightness)	a^* (red/green)	b^* (yellow/blue)
T0	27.97 ± 2.35	5.50 ± 0.40	14.73 ± 0.99
T1	22.23 ± 3.79	3.83 ± 1.04	11.63 ± 2.33
T2	21.50 ± 3.17	3.80 ± 0.77	11.03 ± 1.99
T3	19.63 ± 1.03	3.63 ± 0.15	9.93 ± 0.66

Values are represented as mean ± SD (n = 10). Means with different letters varied significantly. T0 = 0% papaya pulp and leaf powder, T1 = 2.5% papaya pulp powder, T2 = 5% papaya pulp powder, T3 = 7.5% papaya pulp powder. All the formulations have same 0.5% papaya leaf powder content.

Figure 2: Papaya pulp and leaf–based energy bars

Sensory Evaluation

The sensory evaluation included the parameters like texture, color, taste, aroma, aftertaste and overall acceptability (Figure 3). The sensory evaluation, conducted on a 9-point hedonic scale by a panel of 20 semi-trained assessors, revealed that consumer acceptability was well-maintained

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across all formulations, with T1 and T2 achieving the most favorable scores. The control bar (T0) achieved the highest scores for taste and overall acceptability (score 8), consistent with its familiar flavor profile from date, apricot, and chickpea, without the slightly bitter and astringent notes introduced by papaya leaf powder. T1, with moderate papaya incorporation (2.5% pulp + 0.5% leaf), achieved high overall acceptability (score approximately 7.5), indicating that the functional enhancement achieved at this level can be delivered without meaningful compromise to sensory quality. This represents a particularly important practical finding: T1 demonstrates the feasibility of delivering measurably improved antioxidant activity (+17.29% DPPH over T0) and enzyme inhibition (+12.2% α-glucosidase over T0) while maintaining consumer acceptability comparable to control. T3, which exhibited the strongest functional profile across all biochemical parameters, demonstrated a slightly lower but still acceptable overall acceptability score.

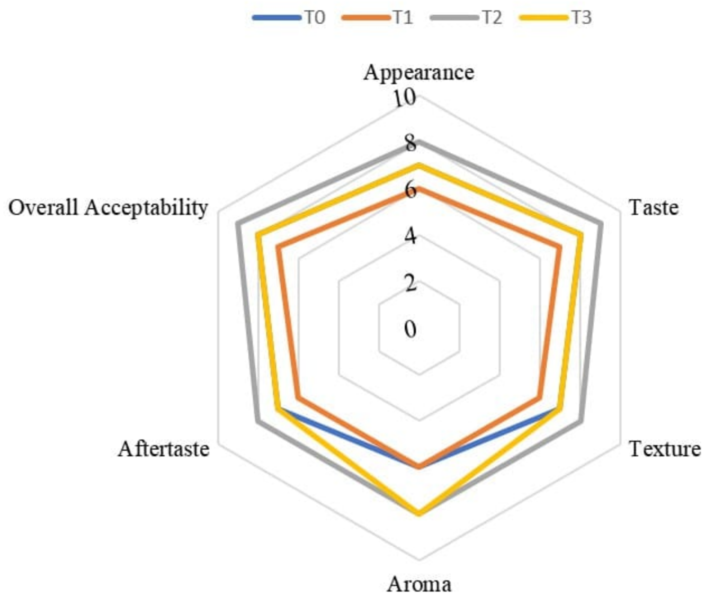

Figure 3: Sensory evaluation of papaya pulp and leaf-based bars

DISCUSSION

Functional snack bars are innovative products with enhanced bioactive and nutritional potential that are perfect to consume for both children and adults. The development of customers interest related to food products has changed since consumer preferred the products made from natural ingredients that offer health benefits. The use of ingredients with bioactive potential and exhibiting anti-inflammatory and anti-oxidative properties influence the cellular and physiological activities in the body and can impart positive influence on health and well-being. Given the increasing burden of T2DM due to excessive caloric intake, sedentary lifestyle and insulin resistance, extensive research is required that how dietary strategies can complement pharmacological interventions. Development of snack foods incorporated with bioactive ingredients are a promising strategy and is consumer acceptable. In current study, functional snack bars were developed containing roasted chickpea powder, date and apricot paste as a base ingredient enriched with papaya pulp powder and papaya leaf powder. The findings revealed that inclusion of papaya leaf and papaya pulp influenced the nutritional, physical and bio-functional potential of the developed bars.

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The papaya-based bars were evaluated for their proximate composition. This study's outcomes revealed that the treatment bars showed the elevated moisture content due to increase in papaya pulp powder. Similar findings were reported that as the proportion of fruit pulp increase in the bars, the moisture content of the bars also increased. This increase was due to the fiber content present in the bar which enhanced the water binding capacity of the bars (Karim et al., 2024). A study based on fruit-based snack bars reported that bars made from papaya and banana showed the moisture content of 7.8%–10.8%. This showed a positive correlation with the fruit pulp used in that bar (Ikuomola et al., 2017). The papaya leaf contributed to the high ash content in the study as compared to the papaya fruit pulp and seeds. This showed that the leaf contributed to the high mineral content due to accumulation of minerals in their vegetative tissues (Moses and Olanrewaju, 2018). For the protein content, the previous research on nutritional assessment of papaya pulp and leaf showed that the papaya leaf has the highest protein content as compared to the pulp (Kanadi et al., 2021). These studies emphasized that the papaya leaf concentration present in our formulations contributed to protein content in the bars. For fat concentration, our finding reports an increase in fat content with increase in papaya pulp concentration in snack bars. The previous research on nutritional assessment of papaya pulp and leaf showed that the papaya leaf has the highest protein content as compared to the pulp (Kanadi et al., 2021). These studies emphasized that the papaya leaf concentration present in our formulations contributed to protein content in the bars. The carbohydrate content decreased as the base ingredient wheat flour and chickpeas decreased in the formulations. The bars containing no any functional ingredient but the base ingredient chickpea powder contributed to the high carbohydrate content (Bautista-Villarreal et al., 2025). The study on snack bar contained chickpea powder showed the highest carbohydrate content of 50% in the bar.

The antioxidant assay revealed that with increase in concentration in bars (T1–T3), a progressive increase in scavenging activity was observed, signifying that phenolics and flavonoids in papaya directly contribute to functional bar's ability to neutralize radicals. Papaya's bioactives were effective in increasing the antioxidant activity of the developed bars. Likewise, Papaya pulp and leaf extracts present in formulations showed significant reducing capacity when assessed by FRAP. Multiple findings reported the strong DPPH radical scavenging activity of papaya pulp and leaf extracts (Asaduzzaman et al., 2020). Previous studies have reported that the addition of papaya pulp in the formulations exhibited the high DPPH scavenging activity (Addai et al., 2016). Another study reported that bars containing dried papaya pulp retained more of its scavenging capacity and an excellent antioxidant source (Jeon et al., 2022). As papaya powders are rich sources of phenols and other bioactive compounds. These compounds enhanced the scavenging activity of free radicals when added in bars. The total phenolic content varied in previous studies according the extraction method, part of papaya used and the type of papaya. The TPC content in those bars ranged from 235–2070 mg GAE/100g. The highest Phenolic content was seen in the bars containing papaya leaf followed by papaya seeds and pulp (Sharma et al., 2022). As far the flavonoid content is concerned, the control group showed the lowest flavonoid content as compared to the papaya enriched functional bars. High levels of quercetin and kaempferol present in papaya contribute to antioxidant potential of functional snack bars (Nugroho et al., 2017). Our findings are consistent with the well-characterized phytochemical richness of *Carica papaya*, which contains phenolic acids including chlorogenic, ferulic, caffeic, and myricetin, alongside flavonoids such as quercetin and kaempferol, and other bioactive compounds including carotenoids and tocopherols. Papaya leaf powder (84.70%) demonstrated markedly superior antioxidant activity compared to papaya pulp powder (86.44%), and its incorporation at even the low concentration of 0.5% contributed meaningfully to the antioxidant enhancement observed

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across T1 to T3.

The in vitro antidiabetic potential of the bars was assessed via inhibition of α-amylase and α-glucosidase, two key carbohydrate-hydrolyzing enzymes that regulate the rate of glucose absorption in the gastrointestinal tract. Inhibition of these enzymes is a clinically validated mechanism for reducing postprandial hyperglycemia, analogous in principle to the pharmacological action of acarbose, a first-line antidiabetic agent. The enzymatic inhibition assay showed that the papaya enriched bars significantly inhibited the activity of both α-amylase and α-glucosidase. Similar studies demonstrated that papaya leaf and pulp extracted in ethanol showed high α-amylase inhibition capacity (Peres et al., 2023). Although these values reflect moderate inhibition relative to the highly purified extracts commonly reported in isolated phytochemical studies, it is essential to interpret them in the context of a complex food matrix where bioactive compounds are embedded within a macronutrient-dense environment that inherently moderates bioavailability. Notably, T3 consistently exhibited superior inhibition across both enzymes, confirming that higher papaya pulp concentrations deliver greater antidiabetic functional activity. The impact of papaya pulp powder is more prominent in α-glucosidase assay. This indicated that papaya pulp powder remarkably interacts with α-glucosidase enzyme as compared to α-amylase. So, in both α-amylase and α-glucosidase inhibition assay, papaya leaf powder was the primary driver to inhibit the activity of these enzymes (Abubakar et al., 2019). The sensory evaluation revealed that most participants liked the T0 and T1 in terms of taste, aftertaste and overall acceptability. Other characteristics like texture, aroma and appearance did not show any major difference in all the treatment and control groups. The control group showed the highest viscosity. Moving towards treatments the value of viscosity reduced. When we talk about the adhesiveness property of the bars, T3 shows highest values. Other treatment groups also showed low score in contrast to the T0 group. The control bar showed slight red color and treatments bar indicated green one due to papaya leaf powder. The color of control bar is moderately yellow as there are no papaya pulp and leaf in it. Overall, bars containing papaya pulp powder and leaf powder showed highest antioxidative capacity, phenol contents, flavonoid content, strong in-vitro antidiabetic potential and good overall sensory acceptability.

CONCLUSION

This study successfully developed and characterized four papaya-enriched snack bar formulations incorporating papaya pulp powder and papaya leaf powder alongside roasted chickpea powder, apricot paste, and date paste as a functional food base. The findings demonstrate that progressive incorporation of papaya derivatives significantly and dose-dependently enhances the antioxidant capacity, total phenolic and flavonoid content, and in vitro antidiabetic enzyme inhibitory activity of the bars, with T3 achieving the highest functional performance across all biochemical parameters. Physical characterization confirmed the structural integrity of all formulations, with hardness values maintained consistently despite compositional variation. Sensory evaluation identified T1 as the optimal balance point between functional enrichment and consumer acceptability, achieving meaningfully improved antioxidant and enzyme inhibitory properties while maintaining overall acceptability comparable to control. These findings suggest papaya-enriched snack bars as affordable, accessible, and nutritionally enhanced functional foods with antioxidant and antidiabetic potential relevant to the dietary management of T2DM.

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Development and Characterization of Tamarind Sauce Supplemented with Moringa Leaf Powder

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ABSTRACT

Malnutrition is increasing worldwide, particularly among women and children. The use of fast foods is trending in youth nowadays and sauce is inevitable component of fast food. Moringa leaf powder (1-5%) was used as a supplement in tamarind sauce to provide essential nutrients while plain tamarind sauce considered as control. Supplemented sauce was analyzed for titratable acidity, TSS, pH, antioxidant analysis, bioactive compounds like total phenols and ascorbic acid as well as total plate count during 28 days storage. It was observed that pH (2.11-2.48), TSS (38.64-44.88 °B), ascorbic acid (36.37-40.90 mg/100 g), antioxidant activity (39.28-46.98%) and total phenols (108.38-119.40 mgGAE/100g) increased with the rise in level of moringa leaf powder. Acidity (1.76-1.08 %), color value L (26.22-25.97), a* (4.83-3.98), b* (3.78-3.33) and total plate count (1.68-1.35 log CFU/ml) showed a gradual declining trend in sauce samples with rising level of moringa leaf powder. Sensory evaluation scores varied between 7.89-6.83, 7.46-7.03, 7.36-6.96 and 7.66-6.58 respectively for taste, texture, color and overall acceptability. Sensory perception scores decline with increasing level of moringa leaf powder. T_1 with 1% moringa leaf powder was considered the best based on sensorial scores however leaf powder incorporation up to 3% was acceptable based on sensory perception along with improved nutrient profile.

Keywords: Moringa leaf powder; Tamarind sauce; nutritional properties; antioxidant; sensory quality.

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INTRODUCTION

Fruits and vegetables are essential because these provide minerals, dietary fiber and necessary vitamins to whole population of the world. Despite having limited calories, fruits and vegetables are vital for the development and proper working of human body (Ibe et al., 2020). The main substances in fruits and vegetables are phenolic compounds and antioxidants which provide health promoting benefits and lower the risk of several diseases like cancer (Coman et al., 2020). World Health Organization (WHO) recommends a daily intake of at least 400g fruits and vegetables per person (Ibe et al., 2020).

Globally over 2 billion people suffer from malnutrition with highest prevalence rates in Africa and South Asia (Kukreti et al., 2023). Half of the global population mainly from Africa and Asia face nutrition deficiency owing to their sole reliance on cereals (Vinoth and Ravindhran, 2017). Despite of self-sufficiency in food, 60% population in Pakistan is food insecure. The majority (one-third) of the children in developing countries including Pakistan are malnourished (Sultan and Iram, 2023). Consumption of balanced diet from different food groups with diet diversification and fortification, supplementation or enrichment are available options to combat malnutrition. The supplementation is addition of various nutrients to foods in order to improve the micronutrient status, make fortified products readily available and affordable by population to avoid widespread nutrient shortages and associated deficiencies (Saeed et al., 2021).

Moringa (*Moringa oleifera* L.) is an Indian herb grown in tropical and subtropical regions. It is referred as the miracle tree due to its variety of health promoting attributes like anticancer (Kumar et al., 2023), antidiabetic (Mahmoud et al., 2022), anti-inflammatory (Cuellar-Nunez et al., 2021), hypocholesterolemic (Chen et al., 2020), cardioprotective (Aju et al., 2020), antihypertensive (Acuram et al., 2019), hepatoprotective (Fotio et al., 2020), antibacterial (Berg and Kuipers, 2022) and antioxidant (Mahmoud et al., 2022) characteristics. It is effective to treat skin problems and for weight reduction (Essa et al., 2014). Additionally, it aids in boosting blood antioxidant level, lowering blood sugar and reducing chronic inflammation (Islam et al., 2021). The traditional use of moringa leaves, seeds, immature seed pods, bark, roots, sap and flowers in medicine is widespread.

Being enriched with various functional nutrients like vitamins, minerals, proteins, dietary fiber and phytochemicals including tannins, alkaloids, polyphenols, flavonoids, carotenoids and tocopherols (Ariani et al., 2023) having potential health benefits (Zainab et al., 2020), moringa leaf powder (MLP) is globally known as promising option for fortification to formulate various functional foods. MLP is used as nutritional supplement for children, infants and pregnant woman in regions with food scarcity (Mahato et al., 2022) to prevent protein energy malnutrition (Mune et al., 2016). Minerals including calcium, magnesium, potassium, iron, copper and manganese exist in moringa leaf (Owon et al., 2021). MLP contain 27.4% protein, 5.6% oil and 23.7% dietary fiber which makes it potential food supplement (Cattan et al., 2022). Moringa leaf protein is analogous to egg and milk in quality (Liu et al., 2018) and it contains balanced profile of essential amino acids including lysine, methionine, cysteine and tryptophan (Stadtlander and Becker, 2017). It contains potassium 15 folds higher than bananas, 10 folds greater vitamin-A than carrots, 7 times more vitamin C than oranges, 17 times more calcium than milk and 25 times greater iron than spinach (Rockwood et al., 2013).

Moringa is extensively cultivated for numerous culinary uses like leaves and young seeds are consumed as food items. Moringa leaves find use in vegetable curries, seasoning, pickles, eaten

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as salad greens in fresh form, combined with other grains and vegetables, or cooked as leafy greens like spinach and served as main nutrition course or side dish with other foods (El-Rahim et al., 2017). MLP is used as condiment in spices, sauce and soups, as green teas, amahewu, capsules, yogurt, bread and biscuits (Tafu and Jideani, 2022), sprinkled on other foods to enhance functionality and nutritive value, as supplement, incorporated in health promoting herbal teas or mixed with cold or hot drinks (El-Rahim et al., 2017).

Tamarind (*Tamarindus indica* L.) is tropical fruit and member of Leguminosae family, originated from Africa. It is known as Imli "Indian date" or "Assam tree". Tamarind tree is hardy in nature, can be grown on marginal lands with minimal care even in absence of irrigation (Vidal-Tovar et al., 2022). Fruit comprised of 55% pulp, 34% seed, and 11% shell and fiber (Sudha et al., 2022). Pulp contains higher quantity of carbohydrate, fiber, protein, calcium, iron, phosphorus, vitamin B_2 and C (Abdi and Serrem, 2013). The World Health Organization (WHO) reported presence of all essential amino acids excluding tryptophan in tamarind pulp. Tamarind pulp is used as snack and an imperative ingredient in preparation of various culinary dishes, sauce, curry, chutneys, fish pickle locally known as tamarind fish in India (Toungos, 2019), pulp powder, tamarind juice concentrate, candy, jam, syrup, porridge souring ingredient, seasoning and flavoring. Different high value ingredients like pectin, tartaric acid and alcohol can be derived from pulp (Narina et al., 2019). Refreshing drink made from tamarind pulp is available from street vendors during summer everywhere in Pakistan. Sweetened pulp is used confectionary, carbonated or noncarbonated drink popular in Mexico, Puerto Rico and Guatemala (Toungos, 2019). Tamarind pulp is carminative and laxative whereas its extract is used as antimicrobial to combat secondary bacterial infections in human (Narina et al., 2019a).

Sauce is coined from Latin word "salsas" meaning salted, is semi solid or liquid food used to relish fish, poultry, meat, vegetables and deserts to enhance nutritional value, appeal, richness, moistness and to garish foods (Ozolina et al., 2019). Sauce offers harmony and balance to the meal it is served with. Although sauces and ketchup have no significant differences from one another, however, acidity and TSS can be used to differentiate both products. Sauces are often thicker with higher total soluble solids (at least 30%) than ketchup (at least 28%). Fruit sauces are gaining popularity because these enhance functional properties of foods and are becoming imperative food ingredient in every cuisine (Levent and Alpaslan, 2018). The use of fast foods is trending among youth and children nowadays. The sauce is inevitable component of fast foods which are most popular due to changing life style and busy work schedule. Moringa leaf powder is cheap source for prevention of anemia, malnutrition and diverse pathological issues like mineral and vitamin associated child blindness (Peñalver et al., 2022). Keeping in view therapeutic and nutritional benefits of tamarind and moringa leaf powder, MLP supplemented tamarind sauce was developed to improve nutritional profile and evaluate sensory attributes.

MATERIALS AND METHODS

Procurement of raw materials

This study was conducted at the Fruit and Vegetable Laboratory, National Institute of Food Science and Technology, University of Agriculture, Faisalabad. Fresh moringa leaves were collected from the University of Agriculture, Faisalabad, whereas tamarind and the remaining raw materials required for sauce preparation were purchased from the local market of Faisalabad.

DOI: https://doi.org/10.65749/pjfs.2026.30.1.0006

Preparation of moringa leaf powder

Fresh moringa leaves were de-stemmed and washed thoroughly with water to remove adhering dirt and foreign matter. The cleaned leaves were dipped in 1% saline solution to reduce surface microbial load and then rinsed with distilled water. For color retention, the leaves were treated with 0.1% potassium metabisulphite solution for 15 min. Thereafter, the solution was drained, and the leaves were shade-dried on aluminum trays followed by dehydration at 75°C until the moisture content reached 6–8%. The dried leaves were ground to obtain a fine powder, which was used for product development.

Preparation of tamarind pulp and moringa leaf powder supplemented tamarind sauce

Dehydrated tamarind was cleaned and soaked in warm water for 15–20 min to soften the pulp. The seeds and outer skin were removed, and the pulp was strained through a fine-mesh sieve to obtain a smooth tamarind base. Tamarind sauce was then prepared by adding water to the pulp and cooking the mixture at 100°C for 30 min. Moringa leaf powder was incorporated according to the treatment plan by replacing tamarind pulp at 0, 1, 2, 3, 4, and 5%, corresponding to treatments T0, T1, T2, T3, T4, and T5, respectively. Red chili, black pepper, salt, and sugar were added according to the treatment plan, and the mixture was further cooked until the desired total soluble solids were achieved. Sodium benzoate was added at the end of cooking, and the sauce was removed from heat. Vinegar was added immediately before filling, following the method described by Manjula et al. (2017). Plain tamarind sauce without moringa leaf powder served as the control. The prepared samples were stored under ambient conditions for 28 days and analyzed at 7-day intervals (0, 7, 14, 21, and 28 days). All analyses were performed in triplicate.

Table 1: Treatment plan for tamarind sauce supplemented with moringa leaf powder

Treatment	Tamarind pulp (%)	Moringa leaf powder (%)
T_0	100	0
T_1	99	1
T_2	98	2
T_3	97	3
T_4	96	4
T_5	95	5

Proximate analysis of moringa leaf powder

The proximate composition of moringa leaf powder was determined using AOAC (2016) following respective methods 950.46B (moisture), 920.153 (Ash), 963.15 (Crude fat by Soxhlet method), crude fiber, 928.08 (crude protein by Kjeldhal's method).

Color, TSS, acidity, pH and ascorbic acid of MLP supplemented tamarind sauce

Color and TSS of moringa leaf powder supplemented tamarind sauce were determined using colorimeter and digital refractometer (Din et al., 2020). Acidity and pH were determined

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following their respective methods as described by AOAC (2016) and Zeeshan et al. (2017). Ascorbic acid of MLP supplemented tamarind sauce was determined according to Pavani et al. (2022) using following formula:

$$\text{Ascorbic acid (mg/100 g)} = \frac{1 \times R \times V}{R_1 \times W \times V_1} \times 100$$

where R_1= dye vol. used in titration with standard solution, W= Weight of sample, R= sample used, V= sample vol. made with 0.4% oxalic acid = 100, V_1= sample vol. taken from 100 ml =10 ml.

Sample extraction for antioxidant activity and total phenolic contents

One gram MLP supplemented tamarind sauce was mixed with 10 mL methanol in a test tube. It was homogenized, sonicated for 15 minutes and centrifuged for 10 minutes at 2500 rpm. Supernatant was used for antioxidant capacity measured as percent inhibition of free radical using 2, 2 diphenyl-1-picrylhydrazyl whereas Folin-Ciocalteu colorimeter method was used to measure the total phenolic contents (Campos-Montiel et al., 2022).

$$\text{Radical scavenging activity } (\%) = \frac{\text{Control OD} - \text{Sample OD}}{\text{Control OD}} \times 100$$

Microbial Analysis (Total Plate Count)

Total plate count of moringa leaf powder supplemented tamarind sauce was determined according to Hekmat et al. (2015) using nutrient agar medium. Briefly, 1 g of sauce sample was aseptically transferred into 9 mL sterile normal saline to obtain the initial dilution, and subsequent ten-fold serial dilutions were prepared under aseptic conditions. Aliquots from appropriate dilutions were plated on nutrient agar plates and incubated at 37°C for 24 h. After incubation, the developed colonies were counted using a colony counter, and the microbial load was calculated by multiplying the average colony count by the corresponding dilution factor. The results were expressed as log CFU/mL and used for statistical analysis.

$$\text{Total plate count} = \text{dilution factor} \times \text{average number of colonies}$$

Sensory evaluation

Sensory evaluation of moringa leaf powder supplemented tamarind sauce was conducted at different storage intervals (0, 7, 14, 21, and 28 days) using a 9-point hedonic scale where 9 = like extremely and 1 = dislike extremely. The samples were evaluated for color, taste, texture, and overall acceptability. Sauce samples from each treatment were presented to the trained panelists under uniform conditions. Mineral water was provided for mouth rinsing between samples to minimize the residual effect of the previous sample. The sensory scores obtained for color, taste, texture, and overall acceptability were used to determine consumer preference for the supplemented tamarind sauce during storage (Meilgard et al., 2016).

Statistical analysis

The experiment was conducted using a two-factor factorial arrangement under a completely randomized design (CRD), in which treatment (T_0–T_5) and storage interval (0, 7, 14, 21, and

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28 days) were considered as the main effects. The data obtained for the physicochemical, antioxidant, microbial, and sensory attributes of moringa leaf powder supplemented tamarind sauce were statistically analyzed using Statistix 8.1 software. Mean comparisons were performed using Tukey's honestly significant difference (HSD) test at $p \leq 0.05$. The results are presented as mean $\pm$ standard deviation of three replicates for each treatment at each storage interval.

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RESULTS AND DISCUSSION

Proximate composition of moringa leaf powder

The means for proximate composition of moringa leaf powder revealed 7.4 ± 0.05 % moisture, 25.4 ± 0.4 % crude protein, 6.49 ± 0.03% crude fat, 9.82 ± 0.02% ash, 12.45 ± 0.03 % crude fiber and 38.94 ± 0.02 % NFE (Table 2).

Proximate composition of *M. oliefera* leaf powder plays a significant and crucial role regarding the quality and nutritional significance of moringa-supplemented products. The results are in line with Bourekoua et al. (2018) who reported that moringa leaves contain moisture 5.62 %, fat 5.41%, protein 23.29%, fiber 27.85%, and NFE 37.83%. In another study, it was revealed that moringa leaf powder comprise of 12.48% crude fiber, 10.75% moisture, 6.49% crude fat, 7.79% ash and 23.72% NFE (Mushtaq et al., 2018). The change in the proximate composition of moringa leaf powder was due to different varieties, environmental conditions and processing techniques.

Table 2: Proximate composition of moringa leaf powder

Proximate composition (Parameters)	**Results (%)**
Moisture	7.4 ± 0.05%
Fiber	12.45 ± 0.03%
Fat	6.49 ± 0.03%
Protein	25.4 ± 0.4%
Ash	9.82 ± 0.02%
NFE	38.94 ± 0.02%

Total soluble solids of MLP supplemented tamarind sauce

The sugars, acids and other soluble ingredients found in any fruit and vegetable constitute total soluble solids (TSS). The acidity of tamarind decreases by increasing the total soluble solids. In all food industries especially fruits and vegetables industry preparing sauces, juices, jams and beverages, TSS is an important parameter. Treatments, storage and their interaction exerted a highly significant (p¡0.01) effect on TSS value of MLP supplemented tamarind sauce. TSS increased with increase in storage time and levels of moringa leaf powder (Fig. 1). The highest TSS was noted in T_5 (44.88°B) while lowest in T_0 (38.64°B). The TSS value of MLP supplemented tamarind sauce increased significantly from 39.10°B at day zero to 43.85°B on 28th day. The increase in TSS was due to acid hydrolysis and breakdown of complex carbohydrates into sugars. TSS increased linearly from T_1 to T_5 with rise in level of MLP addition in tamarind sauce.

Berna et al. (2013) concluded that sauce has TSS ranging from 30.05 to 45.30 °B in rowanberry and rowanberry-pumpkin sauce. Din et al. (2020) reported TSS value in moringa root supplemented tomato sauce was 24.90 to 28.50 °B and showed increasing trend in TSS with rise in moringa root level which is consistent with current study results. Javed et al. (2022) observed the lowest TSS in control (tomato sauce) at start of storage which increased gradually till end.

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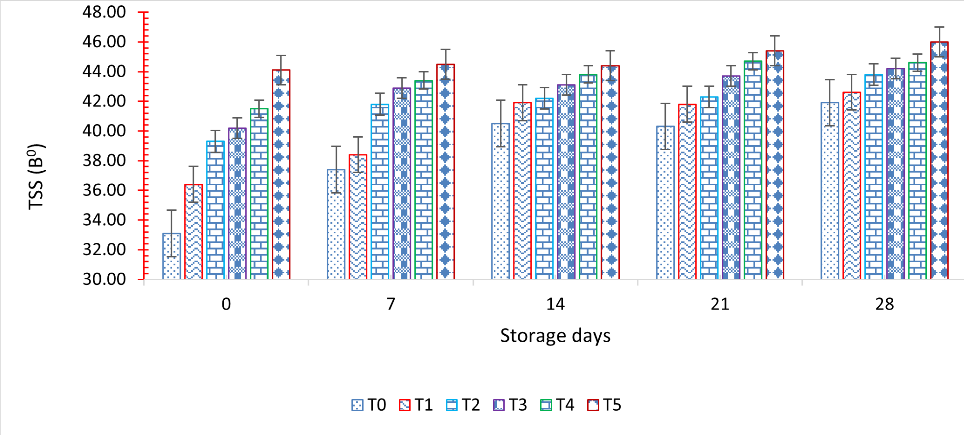

Figure 1: TSS of MLP supplemented tamarind sauce during storage

Titratable acidity of MLP supplemented tamarind sauce

Treatments and storage intervals had a highly significant (p ¡ 0.05) effect on the titratable acidity of moringa leaf powder supplemented tamarind sauce, while their interaction was also significant. The highest mean titratable acidity among treatments was recorded in T0 (1.77%), whereas the lowest value was observed in T5 (1.09%). A progressive decline in acidity was noted with increasing supplementation level of moringa leaf powder, indicating an inverse relationship between titratable acidity and moringa leaf powder concentration in tamarind sauce. The mean acidity values of T1, T2, T3, and T4 were 1.38, 1.33, 1.29, and 1.22%, respectively (Fig. 2). In contrast, storage resulted in a gradual increase in titratable acidity, with the lowest mean value recorded at day 0 (1.21%) and the highest at day 28 (1.48%). The increase in titratable acidity during storage may be attributed to the conversion of organic compounds into organic acids.

Aroma and taste in fruit-based products are influenced by volatile compounds, sugars, organic acids, and the sugar-acid balance, while acidity also contributes to product stability against spoilage. Rajput et al. (2017) similarly reported that increasing the supplementation level of moringa leaf powder reduced the acidity of jam from 0.66 to 0.44%. Likewise, Din et al. (2020) observed that acidity in moringa root supplemented tomato sauce decreased from 2.83% in the control to 1.59% with increasing moringa root addition, although acidity increased during storage. Javed et al. (2022) also reported that titratable acidity in sauce decreased with increasing incorporation of carrot pulp but increased with storage time, which was attributed to sugar oxidation, polysaccharide breakdown, and degradation of pectic substances.

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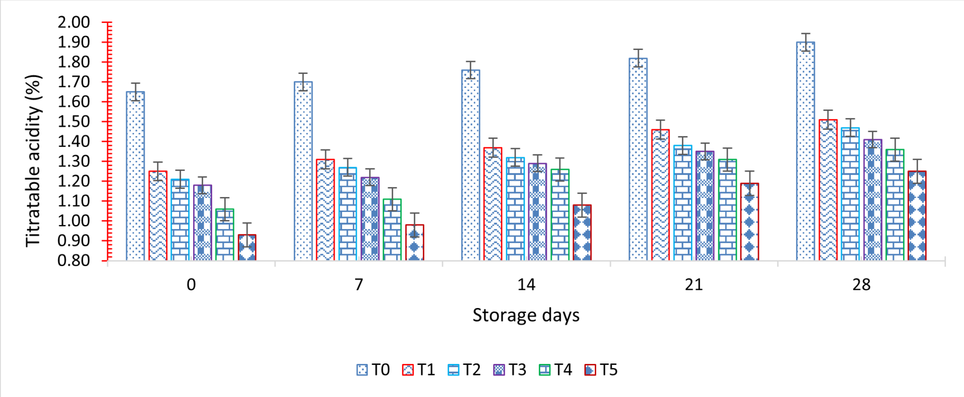

Figure 2: Titratable acidity of MLP supplemented tamarind sauce during storage

The pH values of MLP supplemented tamarind sauce

pH is an important quality attribute that influences the palatability, processing stability, and storage behavior of fruit-based products. The level of moringa leaf powder supplementation and storage interval exerted a highly significant (p ¡ 0.05) effect on the pH of tamarind sauce, while their interaction was also significant. The mean values among treatments showed that pH increased progressively with increasing concentration of moringa leaf powder. The highest pH was recorded in T5 (2.48), whereas the lowest pH was observed in T0 (2.11) (Table 3). This increase in pH with moringa leaf powder supplementation may be attributed to the partial replacement of the acidic tamarind pulp matrix and the consequent reduction in overall acidity of the sauce system. During storage, however, pH decreased gradually, with the maximum mean pH observed at day 0 (2.41) and the minimum at day 28 (2.19). The decline in pH during storage may be associated with the formation of acidic compounds resulting from the degradation of polysaccharides and related constituents, thereby creating a more acidic environment.

Amengor et al. (2017) reported that the minimum value of pH 5.32 in control whereas among dishes supplemented with MLP, pH significantly increased to 5.35. Din et al. (2020) illustrated that the pH of tomato sauce decreased from 4.55 to 2.67 during three months storage. Kamble et al. (2019) revealed that the addition of moringa leaf powder in soup increased the pH value from 6.3 to 6.5. The pH decreased from 4.38 to 4.09 during 30 days of storage in tomato ketchup supplemented with date pulp (Rajput et al., 2017) which is similar to pH values of tamarind sauce in current research. The decline in pH during storage may be ascribed to increasing microbial population and oxidative disintegration of complex compounds in addition to biochemical changes owing to environmental factors (Javed et al., 2022).

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Table 3: The pH values of MLP supplemented tamarind sauce during storage

Treatments	Storage days					Mean
	0	7	14	21	28	
T_0	2.21 ± 0.02^l	2.16 ± 0.03^n	2.11 ± 0.02^o	2.07 ± 0.02^q	2.02 ± 0.01^r	2.11^f
T_1	2.27 ± 0.02^j	2.22 ± 0.01^k	2.17 ± 0.02^m	2.11 ± 0.03^o	2.08 ± 0.02^p	2.17^e
T_2	2.38 ± 0.01^e	2.32 ± 0.01^h	2.26 ± 0.01^j	2.19 ± 0.01^l	2.15 ± 0.03^n	2.26^d
T_3	2.44 ± 0.02^c	2.41 ± 0.02^d	2.36 ± 0.04^f	2.29 ± 0.02^i	2.22 ± 0.02^k	2.34^c
T_4	2.56 ± 0.02^ab	2.50 ± 0.02^b	2.45 ± 0.02^c	2.38 ± 0.02^e	2.29 ± 0.02^i	2.44^b
T_5	2.61 ± 0.03^a	2.55 ± 0.02^ab	2.49 ± 0.01^b	2.43 ± 0.03^d	2.35 ± 0.02^g	2.48^a
Mean	2.41^a	2.36^b	2.31^c	2.25^d	2.19^e	

Means having the same letters within a columns or rows do not differ significantly (p0.05)

Color of tamarind sauce supplemented with moringa leaf powder

Food color is an important attribute appreciated by consumers and main factor for acceptance of products. It is an excellent indicator of maturity, ripening, growth phases and quality changes occurring during the processing and storage of fruits and vegetables.

L value

Treatments, storage days and their interaction exerted highly significant (p¡0.05) on L values of moringa leaf powder supplemented tamarind sauce. The highest L value observed in control i.e. T_0 (26.23) followed by T_1 (26.16) and the lowest value attained by T_5 (25.98). With the increase in concentration of moringa leaf powder in tamarind sauce L value decreased that revealed that there was an inverse relationship between L value and MLP concentration. The maximum value was recorded for T_0 and minimum in T_5. In case of storage duration, the highest value (L) was observed at zero days (26.44) which declined to minimum (25.77) on 28^{th} day (Table 4). The maximum color change was examined in sauce samples analyzed during the last storage interval. The declining trend in L values with increase in storage may be due to Millard's reaction that ultimately decreased the brightness of the sauce during storage.

Morsy et al. (2022) reported decline in L value in processed cheese made from milk of ewes-fed diets supplemented with *M. Oleifera* or *Echinacea purpurea* increase with level of incorporation. The current study has close conjunction with Khan et al. (2023) who reported decreasing trend of color values with rise in supplementation level of whole wheat flour with MLP in leavened bread. The reduction in L value during storage may be ascribed to color darkening owing to presence of spices especially ginger in sauce (Jayashree et al., 2012).

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Table 4: L values of MLP supplemented tamarind sauce during storage

Treatments	Storage days					Mean
	0	7	14	21	28	
T_0	26.54±0.02[a]	26.43±0.01[c]	26.19±0.01[i]	26.05±0.02[k]	25.93±0.02[m]	26.22[a]
T_1	26.51±0.02[a]	26.37±0.02[d]	26.15±0.03[j]	25.96±0.02[l]	25.83±0.02[q]	26.16[b]
T_2	26.48±0.01[b]	26.38±0.02[d]	26.13±0.02[j]	25.91±0.01[n]	25.77±0.02[r]	26.13[c]
T_3	26.42±0.01[c]	26.34±0.02[f]	26.06±0.03[k]	25.86±0.01[o]	25.74±0.02[s]	26.08[d]
T_4	26.36±0.02[e]	26.27±0.01[g]	25.94±0.02[m]	25.84±0.02[p]	25.71±0.03[t]	26.02[e]
T_5	26.33±0.03[f]	26.23±0.03[h]	25.91±0.02[n]	25.77±0.03[r]	25.64±0.02[u]	25.97[f]
Mean	26.440[a]	26.336[b]	26.063[c]	25.898[d]	25.770[e]	

Means having the same letters within a columns or rows do not differ significantly (p0.05)

a* value

Treatments, storage and interaction exerted highly significant (p¡0.05) effect on a* value. The maximum a* value was noted for T_0 (4.83) whereas the minimum value in T_5 (3.98) sauce with highest level of moringa leaf powder supplementation. With the increase in the concentration of moringa leaf powder in tamarind sauce, a* value decreased depicting inverse relation between a* color value and level of incorporation in tamarind sauce. The significant variation in among treatments for a* scores with incorporation of moringa leaf powder was observed with respective mean values 4.61, 4.43, 4.29, 4.150 and 3.98 for T_1, T_2, T_3, T_4 and T_5 (Fig. 3). The decline in a* values represent shift in color tinge towards green as moringa leaf powder has green color and with rise in level of incorporation obvious color changed with declining redness and approaching greenish. Among storage intervals, the highest a* was observed at zero-day (4.55) which significantly reduced to 4.23 at 28^{th} day. The values gradually decline at each subsequent evaluation period showing inverse relation with storage duration. The decreasing trend may be attributed to microbial and chemical reactions taking place in sauce during storage.

This study has close conjunction with Morsy et al. (2022) who revealed decrease in a* values in processed cheese made from ewes milk fed on diets supplemented with the rise in incorporation of *M. Oleifera* or *E. purpurea* in diet. Khan et al. (2023) illustrated that a* value of leavened bread changed with the concentration of moringa leaf powder level. Another study by Abou-Zaid and Nadir (2014) showed that a* value of chocolate and halawa decreased by increasing the concentration of moringa leaf powder. Non-enzymatic browning during storage is mainly responsible for increased redness of sauce. Reactions taking place between various ingredients of sauce at elevated processing temperature result in enhanced redness, decreased yellowness and brightness of sauce (Safal et al., 2022).

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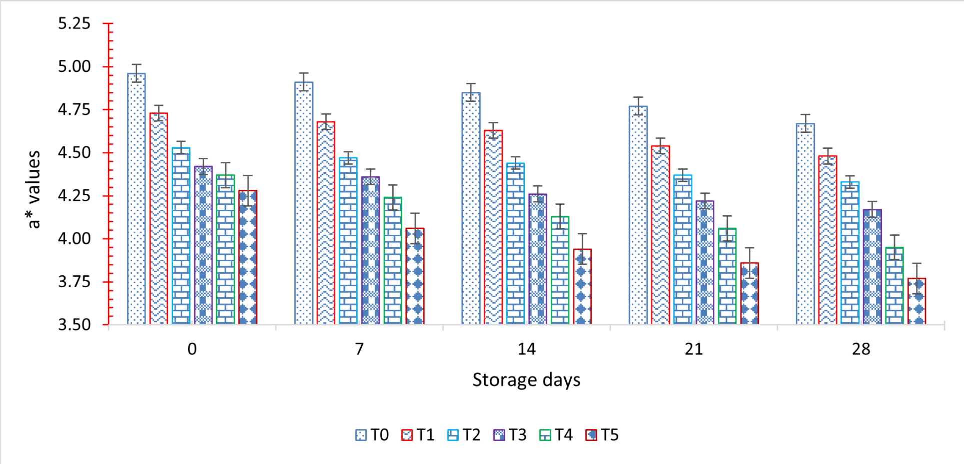

Figure 3: a* values of MLP supplemented tamarind sauce during storage

b* value

Statistical analysis expressed the highly significant (p¡0.01) impact of storage days, treatments and their interaction on the b* value. The highest b* value was recorded for T_0 (3.78), followed by T_1 (3.67) whereas the lowest in T_5 (3.33). Increase in the concentration of moringa leaf powder supplementation in tamarind sauce resulted reduction in b* value revealing an inverse relationship between b* values and moringa leaf powder concentration in tamarind sauce. The variation in treatments with MLP incorporation was observed with respective mean values (3.67), (3.59), (3.48) and (3.44) for T1 to T5. The b* scores were decreased with proportionate rise in level of moringa leaf powder concentration. Regarding storage intervals, the highest b* value was observed at zero day (3.71), which gradually reduced to the lowest value 3.38 on 28^{th} day (Table 5).

The results from current research has close relation with those Abou-Zaid and Nadir (2014) who reported that b* value decreased by increasing the concentration of moringa leaf powder in nutritious chocolate and halawa tahinia made with moringa leaf powder supplementation. During storage color pigments are degraded which ultimately result in production of dark color of the moringa leaf powder-supplemented products. Morsy et al. (2022) concluded that the b* value decreased proportionately in processed cheese made from milk of ewes fed on diets supplemented with increasing concentration of *M. Oleifera* or *E. Purpurea*. In another study Khan et al. (2023) illustrated that the b* value of wheat flour leavened bread declined with the increasing concentration of dehydrated moringa leaf powder.

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Table 5: The b* values of MLP supplemented tamarind sauce during storage

Treatments	Storage days					Mean
	0	7	14	21	28	
T_0	3.91 ± 0.02^a	3.83 ± 0.01^c	3.78 ± 0.01^d	3.72 ± 0.02^e	3.65 ± 0.02^g	3.78^a
T_1	3.86 ± 0.02^b	3.76 ± 0.02^d	3.65 ± 0.01^g	3.56 ± 0.01^i	3.52 ± 0.03^k	3.67^b
T_2	3.74 ± 0.01^e	3.68 ± 0.02^f	3.63 ± 0.02^h	3.54 ± 0.02^j	3.36 ± 0.04^o	3.59^c
T_3	3.63 ± 0.02^h	3.57 ± 0.02^i	3.47 ± 0.02^l	3.43 ± 0.02^m	3.31 ± 0.02^q	3.48^d
T_4	3.63 ± 0.02^h	3.52 ± 0.03^k	3.42 ± 0.02^m	3.37 ± 0.01^o	3.27 ± 0.02^r	3.44^e
T_5	3.48 ± 0.03^l	3.41 ± 0.01^n	3.33 ± 0.01^p	3.27 ± 0.02^r	3.17 ± 0.01^s	3.33^f
Mean	3.71^a	3.63^b	3.55^c	3.48^d	3.38^e	

Means having the same letters within a columns or rows do not differ significantly (p0.05)

Antioxidant activity of MLP supplemented tamarind sauce

Oxidation in foods is prevented by inherent or added antioxidants. Oxidation is a chemical reaction that produces free radicals which spoils the quality of fresh produce and is harmful to the cells of fruits and vegetables. The antioxidant activity of moringa leaf powder was 58.62% based on inhibition percentage of DPPH free radicals.

The results displayed highly significant (p ¡ 0.01) effect of treatments, storage days and their interaction on antioxidant activity of moringa leaf powder supplemented tamarind sauce. Mean values for the treatments with moringa leaf powder supplementation revealed that T_5 (46.99 %) exhibited the highest value of the antioxidant activity whereas the minimum value in T_0 (39.28 %) (Fig. 4). The antioxidant activity increased with the increase of concentration of moringa leaf powder in tamarind sauce. The antioxidant activity showed increasing trend among treatments linearly with rise in level of incorporation which is ascribed to higher antioxidant power of moringa leaf powder. In case of storage, the highest value (46.49 %) for antioxidant activity was observed at zero day which gradually decreased at subsequent evaluation intervals to the minimum value (39.41 %) on 28^{th} day. Storage time was inversely related with antioxidant activity as the antioxidant activity decreased with increase in length of storage and decline may be attributed to synthesis of free radicles during storage owing to various fluctuations and these radicles chemically neutralize inherent antioxidants. With the passage of time these free radicles accumulate in fresh produce and are quenched by antioxidants which in turn decrease in amount leading to lower antioxidant potential at later evaluation intervals during storage.

The present study had a close relationship with Shokry's (2017) research and findings for antioxidant activity in current study are consistent with DPPH based antioxidant activity which increased from 43.3 to 88.1 (33 mg/ml extract) with an increased percentage of moringa leaf powder in olive moringa paste and garlic moringa paste. Ajibola et al. (2015) reported that DPPH radicle scavenging activity was 40.56 (%) in control which increased gradually to 78.96 (%) with an increased % of moringa leaf powder in biscuits. This study has similarities with Mushtaq et al. (2018) who noted that DPPH activity was 64.32% in bread without addition of moringa leaves which increased to 80.52% with the rise in level of moringa leaf powder. According to Aderinola (2018), the DPPH radicle quenching activity increased from 16.05% to 88.77% in moringa leaf powder-supplemented smoothies which in agreement with present investigation.

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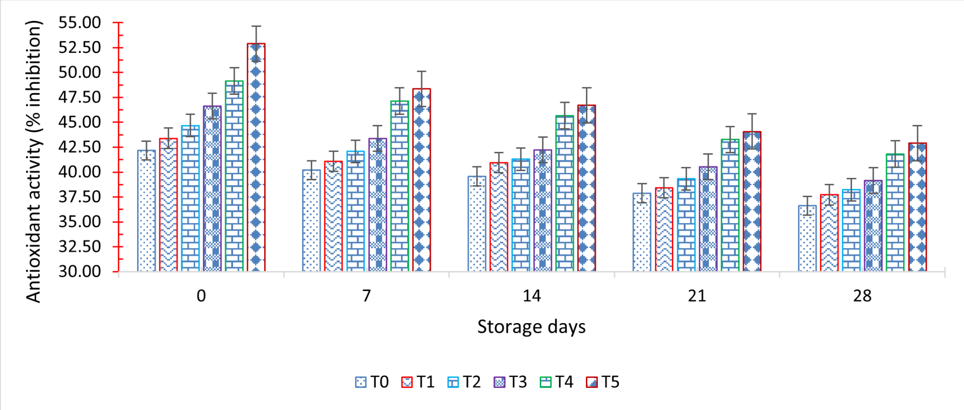

Figure 4: Antioxidant activity of MLP supplemented tamarind sauce during storage

Total phenolic contents (mg GAE/100 g) of MLP supplemented tamarind sauce

Total phenolic contents are very important for our health due to their high antioxidant power. Phenolic compounds protect the human body from cardiovascular diseases. The estimated total phenolic content of moringa leaf powder was 91.37 mg/100g GAE.

The highly significant (p¡0.01) influence of treatments, storage days and their interactions was recorded on total phenolic content of moringa leaf powder supplemented sauce. Comparison of mean values among supplemented treatments revealed that T_5 (119.41mg/100g GAE) exhibited maximum value for total phenol content and on contrary minimum TPC value in T_0 (108.38mg/100g GAE) (Fig. 5). Present study data showed that total phenolic contents increased with the rise in concentration of moringa leaf powder in tamarind sauce. Level of incorporation showed direct relationship between the concentration of moringa leaf powder in tamarind sauce and TPC meaning higher moringa concentration in treatments in turn resulted gradual rise in polyphenols depicting increasing trend. This increment observed in total phenolic content may be ascribed to increasing moringa leaf powder in sauce which is a rich source of phenolic contents.

Among storage intervals, the highest value of total phenolic content was observed at zero days (116.16%) which progressively reduced to 112.34 mg/100g GAE on 28^{th} day. With the passage of time during storage the total phenolic content (mg/GAE) decreased which might be due to use of polyphenols as antioxidants to quench free radicles produced due to storage neglects and high accrual of radicles lead to oxidative stress.

According to Bourekoua et al. (2018), 2.5% supplementation of moringa leaf powder in bread, increased the total phenolic contents from 0.88 to 2.12 GAE/g of dry weight. Mushtaq et al. (2018) concluded that the increased concentration of moringa in supplemented products increases the total phenolic contents from 0.75 to 8.38 mg GAE/g which is in similarity with current research findings. Likewise, Aderinola (2018) studied the same rising trend in TPC with increasing moringa leaf powder concentration in smoothies.

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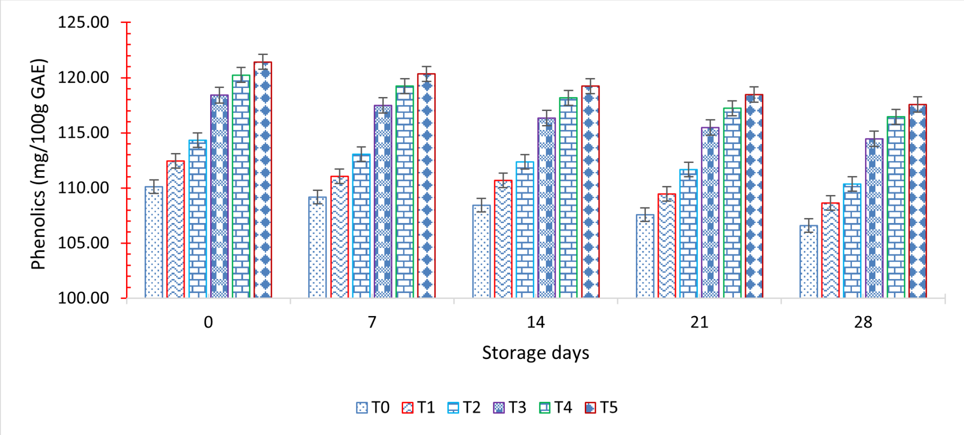

Figure 5: Phenolic compounds of MLP supplemented tamarind sauce during storage

Ascorbic acid (mg/100 g) of MLP supplemented tamarind sauce

Vitamin C is a strong antioxidant that is found naturally fruits and vegetables. Results revealed highly significant (p¡0.01) effect of treatments, storage days and their interactions on ascorbic acid content of moringa leaf powder supplemented tamarind sauce. The mean values among treatments displayed that T_5 contain maximum ascorbic acid (40.91mg/100 g) whereas minimum in T_0 (36.38 mg/100 g). The concentration of ascorbic acid showed gradual rise with increasing level of moringa leaf powder addition in tamarind sauce representing direct association between ascorbic acid content and level of moringa incorporated. The significant variation in ascorbic acid content among supplemented sauce is solely attributed to moringa leaf powder. Contrarily, among storage intervals, the remarkably greater ascorbic acid (39.02 mg/100 g) was recorded on day zero which subsequently decreased to 38.92 mg/100 g on 28^{th} day following gradual decline with the passage of time (Table 6). Hence, ascorbic acid quantity followed converse association with storage duration. It is readily oxidized and more exposure time to oxidants in extended storage as well as increase in free radicles owing to storage neglects lead to lower ascorbic acid level.

Results are in conjunction with those reported by Kachhawa and Chawla (2017) who found that moringa-supplemented products had more contents of ascorbic acid (49.32 mg/100 g) as compared to 12.16 mg/100 g in non-supplemented products revealing increasing trend of vitamin C as the concentration of moringa increased. In another study, Farzana et al. (2017) concluded that vitamin C content increased from 3.2 to 4.6 mg/100 g in vegetable soup with the increasing level of moringa leaf powder supplementation. According to research by Mahmood et al. (2010), 220 mg of ascorbic acid was found in 100 g moringa leaves powder. A study conducted by Din et al. (2020) illustrated that the least value of ascorbic acid 40.60 mg/100 g was observed in tomato sauce without moringa root incorporation which increased to 72.40 mg/100 g in moringa root supplemented tomato sauce. However, literature reviewed show slight decrease in ascorbic acid during 28 days of storage period due long exposure time to pro-oxidants.

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Table 6: Ascorbic acid (mg/100g) of MLP supplemented tamarind sauce during storage

Treatments	Storage days					Mean
	0	7	14	21	28	
T_0	36.43 ± 0.02^{o}	36.40 ± 0.02^{op}	36.38 ± 0.01^{p}	36.35 ± 0.02^{q}	36.33 ± 0.01^{r}	36.37^{f}
T_1	38.59 ± 0.02^{l}	38.54 ± 0.01^{m}	38.51 ± 0.02^{m}	38.48 ± 0.02^{mn}	38.45 ± 0.02^{n}	38.51^{e}
T_2	38.82 ± 0.01^{j}	38.81 ± 0.02^{j}	38.77 ± 0.02^{k}	38.77 ± 0.01^{k}	38.76 ± 0.02^{kl}	38.78^{d}
T_3	39.57 ± 0.02^{g}	39.54 ± 0.02^{g}	39.46 ± 0.03^{h}	39.49 ± 0.03^{i}	39.44 ± 0.01^{h}	39.50^{c}
T_4	39.75 ± 0.03^{d}	39.72 ± 0.02^{d}	39.71 ± 0.01^{de}	39.68 ± 0.02^{e}	39.64 ± 0.02^{ef}	39.70^{b}
T_5	40.95 ± 0.02^{a}	40.93 ± 0.03^{ab}	40.92 ± 0.02^{ab}	40.86 ± 0.02^{c}	40.87 ± 0.02^{bc}	40.91^{a}
Mean	39.02^{a}	38.99^{b}	38.96^{c}	38.94^{d}	38.92^{e}	

Means having the same letters within a columns or rows do not differ significantly (p0.05)

Total plate count of MLP supplemented tamarind sauce

Analysis of variance (ANOVA) depicted highly significant (p¡0.01) effect of treatments and storage days on total plate count whereas interaction effect was significant. Mean values for comparison among treatments (Table 7) revealed the highest value of total plate count in T_0 (1.68) and lowest in T_5 (1.35). Variation in means of all treatments was observed with respective values 1.55, 1.48, 1.43, 1.40 and 1.35 for T_1 to T_5. The mean comparison of storage indicated the lowest total plate count was 0.90 at zero-day which increased to the highest total plate count (2.14) after 28 days. Total plate count gradually rise with length of storage and increase might be due to an enzymatic reaction that gave favorable conditions to microbes for growth.

According to Farzana et al. (2017), moringa supplemented soup powder was acceptable for up to 6 months. The total microbial count ranged between 3.3 x 10^2 to 2.7 x 10^4 CFU/ml during storage. This study also has close conjunction with Amer et al. (2015) who concluded that microbial count was (2.1 × 10^2- 1.2 × 10^2 CFU/ml) at zero day which rise to 2.2× 10^5 (Control) to 1.3× 10^5 CFU/ml in treatment with 2.5% moringa leaf powder addition after 4 months. This research also has similarities with Manaois et al. (2013) who illustrated that rice crackers were shelf stable and microbial counts was in the acceptable range up to 3 weeks and 1% supplementation showed less microbial count 1.25× 10^1 CFU/g. Microbial count rise linearly with duration of storage. As per WHO/FAO established standards, microbial population at 7 log CFU/ml as total plate count is permissible as safe limit for human consumption except coliform, *E. coli* and salmonella (Yim et al., 2019). The results from current study for microbial count are coherent with Sucharitha et al. (2018) who reported 2.27-8.15 log CFU in tomato preserve during 30 days storage. The microbial growth may be attributed to variation in storage conditions and stabilizers used. The carbohydrate content available in food support microbial proliferation (Soma et al., 2009).

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Table 7: Total plate count (log CFU/ml) of MLP supplemented tamarind sauce during storage

Treatments	Storage days					Mean
	0	7	14	21	28	
T_0	1.04 ± 0.01^{lm}	1.36 ± 0.01^{i}	1.61 ± 0.02^{gh}	1.95 ± 0.02^{d}	2.45 ± 0.01^{a}	1.68^{a}
T_1	0.98 ± 0.02^{m}	1.25 ± 0.02^{j}	1.49 ± 0.02^{h}	1.78 ± 0.02^{e}	2.26 ± 0.03^{b}	1.55^{b}
T_2	0.92 ± 0.02^{n}	1.22 ± 0.02^{jk}	1.43 ± 0.03^{h}	1.71 ± 0.03^{ef}	2.13 ± 0.02^{c}	1.48^{c}
T_3	0.86 ± 0.01^{o}	1.15 ± 0.01^{k}	1.39 ± 0.02^{i}	1.69 ± 0.02^{f}	2.06 ± 0.02^{c}	1.43^{d}
T_4	0.84 ± 0.03^{o}	1.16 ± 0.02^{k}	1.36 ± 0.01^{j}	1.65 ± 0.01^{fg}	1.98 ± 0.03^{d}	1.40^{e}
T_5	0.78 ± 0.01^{op}	1.07 ± 0.02^{l}	1.35 ± 0.02^{j}	1.62 ± 0.02^{g}	1.93 ± 0.01^{d}	1.35^{f}
Mean	0.90^{e}	1.20^{d}	1.44^{c}	1.73^{b}	2.14^{a}	

Means having the same letters within a columns or rows do not differ significantly (p0.05)

Sensory evaluation of moringa-supplemented tamarind sauce

The ultimate criteria of any food desirability is mainly based on its sensory quality. Organoleptic attributes of food commodity are the most significant features influencing the product acceptability in market. Overall quality governed by nutritional and other hidden attributes defining sensory quality of any food commodity. Sensory quality has great significance to both the processors and consumers. Overall acceptability is the blend of several senses of observation and perception that are helpful in picking as well as eating a food.

Color

Food color is a significant parameter of quality. Food is firstly perceived with the eye by customer. Color is imperative factor influencing purchase as appealing food color attracts where dull color leads to rejection of food being purchased. Discoloration of food affect the acceptability of the product. Storage, treatments and their interaction exerted highly significant (p¡0.01) effect on color of moringa leaf powder supplemented tamarind sauce. The maximum mean value for sensorial color among treatments was observed in T_1 (7.34), followed by T_0 (7.37) while minimum value in T_5 (7.04). Comparison of mean scores for storages showed the highest value (7.30) was observed at zero days and the minimum score (7.07) on the 28^{th} day of storage (Fig. 6). T_1 was considered the best moringa-supplemented treatment and mostly preferred by the panelist.

Din et al. (2020) concluded that storage of moringa root-supplemented tomato sauce has little effect on color. Color score was 7.52 at zero-day which reduced to 7.33 at 90^{th} day. According to Zungu et al. (2020), color scores was 3.8±1.2 to 2.6±1.5 which reduced with the increased concentration of moringa leaves powder in children's snacks. Sensory color evaluation scores decrease with rise in dose of vegetable-seafood juice in soy sauce (Tang et al., 2023). Abou-Zaid and Nadir (2014) concluded that color scores ranged from 9.5 to 8.3 in chocolate and Halwa and increased concentration of moringa resulted in reduced color score.

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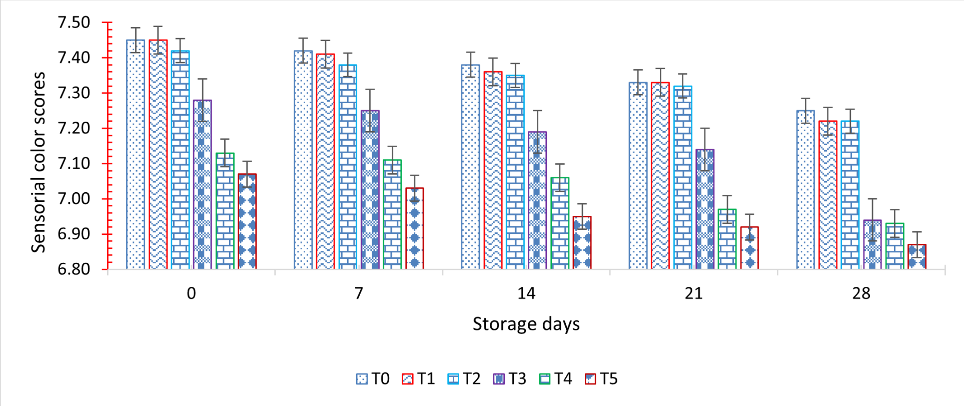

Figure 6: Sensorial color scores of MLP supplemented tamarind sauce during storage

Taste

Analysis of variance (ANOVA) explained the highly significant (p¡0.01) effect of storage, treatment and their interaction on the taste of tamarind sauce supplemented with moringa leaf powder. The present study revealed the highest mean taste score was observed in T_0 (7.90) i.e. control while among MLP supplemented treatments T_1 exhibited significantly higher (7.81) and the minimum score in T_5 (7.00). The mean comparison of storage illustrated that maximum preference score (7.64) was given at zero-day and minimum value (7.42) was observed on the 28^{th} day (Fig. 7). T_1 was considered the best moringa-supplemented treatment and was mostly preferred by the panelist. Whereas treatments with MLP up to 3% were acceptable and beyond this concentration there was pronounced after taste.

According to a study performed by Din et al. (2020) the highest taste score was noted for tomato sauce with lower level of moringa root supplementation. Zungu et al. (2020) concluded that an increased percentage of moringa reduced the taste score from 3.3±1.2 to 3.0+1.1 in children's snacks. Shokry (2017) reported that the taste of moringa-supplemented garlic sauce and olive fruit paste reduced from 9.4 to 8.1 and 9.4 to 8.4 respectively with increased concentration. The best taste score was attained at the lowest concentration of moringa leaf powder in sauce which has similarities with Mawouma et al. (2017).

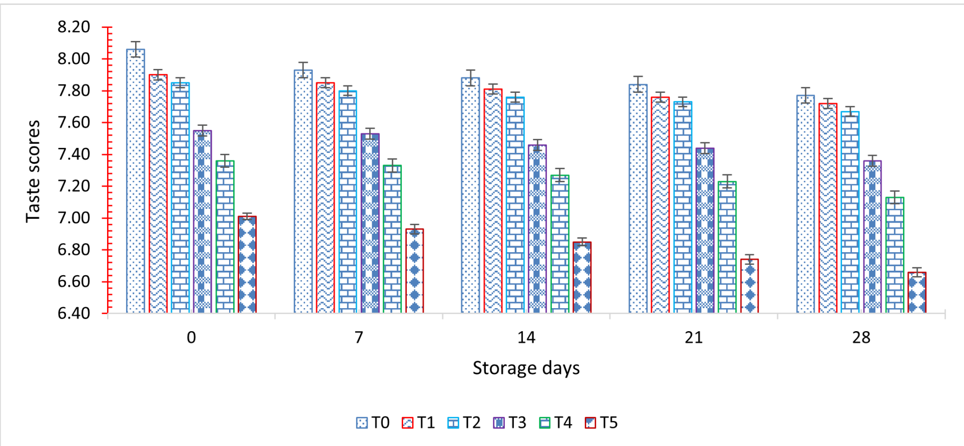

Figure 7: Taste scores of MLP supplemented tamarind sauce during storage

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Texture

Statistical analysis revealed a highly significant effect (p ¡ 0.01) of treatments and storage intervals on the texture of moringa leaf powder supplemented tamarind sauce. The highest mean texture score was recorded in the control treatment, T0 (7.46), while among the moringa leaf powder supplemented treatments, T1 showed the highest score (7.44) and T5 the lowest (7.03). Mean comparison for storage intervals indicated that the maximum texture score was observed at day 0 (7.43), which gradually decreased during storage to 7.18 on day 28 (Table 8). Among the supplemented treatments, T1 was considered the most acceptable in terms of texture and was preferred by the panelists.

Shokry (2017) reported the highest flavor score (9.5) for garlic moringa sauce at a low level of moringa incorporation, whereas higher supplementation reduced the score to 7.9. Similar findings were reported by Mawouma et al. (2017), who observed the highest sensory scores at the lowest moringa supplementation level due to the pronounced aftertaste at higher concentrations. Din et al. (2020) and Kim and Yoo (2012) also reported similar results. Storage duration negatively affected sauce quality irrespective of fruit cultivar and treatment applied, as also observed by Safal et al. (2022).

Table 8: Texture of MLP supplemented tamarind sauce during storage

Treatments	Storage days					Mean
	0	7	14	21	28	
T_0	7.57 ± 0.02^{a}	$7.53\pm0.01^{a}b$	$7.44\pm0.02^{c}d$	7.39 ± 0.01^{e}	7.35 ± 0.02^{h}	7.46^{a}
T_1	7.56 ± 0.01^{a}	7.52 ± 0.02^{b}	$7.42\pm0.02^{d}e$	7.37 ± 0.02^{f}	7.34 ± 0.02^{i}	7.44^{a}
T_2	$7.54\pm0.02^{a}b$	$7.48\pm0.02^{b}c$	7.39 ± 0.03^{e}	7.34 ± 0.02^{i}	7.30 ± 0.01^{k}	7.41^{b}
T_3	$7.42\pm0.02^{d}e$	$7.38\pm0.03^{e}f$	7.33 ± 0.02^{j}	7.26 ± 0.01^{l}	7.23 ± 0.02^{l}	7.32^{c}
T_4	7.31 ± 0.03^{k}	7.36 ± 0.02^{g}	7.27 ± 0.02^{l}	7.09 ± 0.03^{o}	6.96 ± 0.02^{p}	7.19^{d}
T_5	7.18 ± 0.02^{m}	7.13 ± 0.02^{n}	7.03 ± 0.03^{p}	6.93 ± 0.02^{q}	6.87 ± 0.01^{r}	7.03^{e}
Mean	7.43^{a}	7.40^{b}	7.31^{c}	7.23^{d}	7.18^{e}	

Means having the same letters within a columns or rows do not differ significantly (p0.05)

Overall acceptability

Overall acceptability reflects the combined sensory perception of a product in terms of its overall preference. The results revealed a highly significant (p ¡ 0.01) effect of treatments and storage intervals on the overall acceptability of moringa leaf powder supplemented tamarind sauce, whereas their interaction was non-significant. The highest mean overall acceptability score was observed in the control treatment, T0 (7.67), while the score declined progressively with increasing supplementation level of moringa leaf powder and reached the lowest value in T5 (6.58). The reduction in overall acceptability with higher moringa incorporation may be attributed to the pronounced herbal aftertaste and changes in sensory balance at elevated supplementation levels. Storage also caused a gradual decline in overall acceptability, with fresh samples receiving higher scores than those stored for longer periods (Fig. 8). Among the moringa leaf powder supplemented treatments, T1 was considered the most acceptable, while supplementation up to 3% remained acceptable on the basis of sensory perception.

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Similar findings were reported by Mawouma et al. (2017), who observed excellent overall acceptability at lower levels of moringa incorporation in sauce. Kim (2013) also reported good overall acceptability in tomato sauce supplemented with rosemary, whereas Amer et al. (2015) and Manaois et al. (2013) found that moderate supplementation levels of plant powders improved acceptability in bakery and snack products.

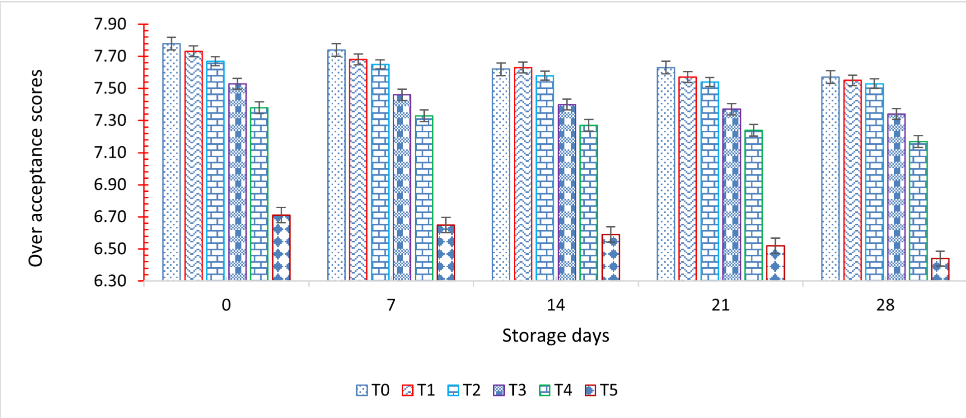

Figure 8: Overall acceptance scores of MLP supplemented tamarind sauce during storage

Malnutrition or micronutrient deficiency is prevalent globally and supplementation with vegetal sources like moringa leaf powder being rich in functional ingredients is promising option to counter it. Tamarind is a cheap product, easily available round the year and affordable, delivers vitamins and minerals to meals in addition to sour flavor. The proximate analysis of moringa leaf powder was done having moisture content (7.4%), fiber (12.45%), crude fat (6.49%), crude protein (25.4%), ash content (9.82 %) and NFE (38.94%). TSS, pH, ascorbic acid, total phenolics and antioxidant activity of moringa-supplemented tamarind sauce showed rising tendency increased with increasing level of MLP addition exhibiting linear relationship while acidity, total microbial count, color (L, a* and b*) showed an inverse relation with MLP dose. Sensory evaluation scores varied (7.90-7.00), (7.46-7.03), (7.37-6.97) and (7.67-7.18) for taste, texture, color and overall acceptability. T_1 obtained the best sensory perception scores on hedonic scale from sensory point of view whereas T_3 showed improved nutritional profile. T_4 and T_5 showed pronounced after taste. T_1 was best based on organoleptic testing however, moringa leaf powder incorporation up to 3% (T_3) was acceptable. With time all sensory parameters showed decreasing scores.

Competing Interests

The authors declare that they have no competing interests.

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Author's contribution

Sidra Bashir performed the methods and investigation and writing of original draft. Muhammad Atif Randhawa conceptualization, supervision of research work and proof read the manuscript.

Zafar Iqbal helped in conceptualization and investigation of the product. Hafiz Muhammad Jawad Saleem helped in writing of this manuscript, statistical software and proof read the manuscript.

Ethical statement

No animals were used or harmed, and the study did not involve clinical or invasive human experimentation.

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