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Valorization of Pomegranate and Banana By-products into Value-added Products: Influence on Physicochemical, Rheological, and Consumer Attributes

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ABSTRACT

Fruits possess a variety of physiologically active compounds including polyphenols, vitamins, essential oils, terpenoids, and minerals, respectively that have ability to prevent disease and promote health. The production of different fruits around the world is 933.1 million metric tons in 2022-24. The global production of banana is around 135 million tons in 2023-2024 and banana peel makes up almost 35-40% of the fruit's weight that accounts for about 36 million tons annually. Moreover, global production of pomegranate and its byproducts reaches around 8.1 million tons annually and around 1.9 million metric tons of pomegranate peels are produced worldwide on annual basis These by-products, rich in dietary fiber, antioxidants, resistant starch, and bioactive compounds, improve the nutritional profile of value-added products, offering benefits such as antioxidant protection, glycemic control, and improved gut health. However, their incorporation significantly influences the physicochemical, rheological, sensorial, and cooking properties of value-added products. This review elaborates the composition and functional potential of pomegranate and banana by-products, their effects on products quality, and the challenges associated with their industrial application. It also highlights the need for advancements in processing techniques such as particle size reduction and encapsulation to mitigate adverse effects on dough behavior, firmness, and consumer acceptability. The paper also emphasizes the importance of understanding synergistic interactions between these by-products and developing consumer-centric products. Future research should focus on long-term stability, industrial scalability, and enhanced functionality through synergistic combinations. Pomegranate and banana by-products hold significant promise as functional ingredients into value-added products such as pasta, bakery items, beverages and functional and nutraceutical ingredients by contributing to sustainable food systems and addressing the growing demand for health-focused, eco-friendly products.

INTRODUCTION

Consumer awareness of health and sustainability is triggering paradigm shift towards the development of functional foods for the global food industry. Functional foods are meant to possess properties such as providing more than one type of nutrient, antioxidant, digestive, metabolic carbohydrate, fiber, lipid, flavonoids, essential fatty acids, vitamins, and minerals, to alleviate health concerns like providing antioxidant defense, digestive health enhancing, and metabolic regulation (Devi *et al.,* 2023). In particular, pasta is an acceptable staple food for many which has high potential for the incorporation of functional ingredients due to its acceptance, easy to produce and high versatility. The incorporation of plant-based by-products into pasta formulations represents a dual advantage: Improve the functional properties of the food product with reduction on food waste (Garg and Rana, 2022).

Fruits possess a variety of physiologically active compounds, including polyphenols, vitamins, essential oils, terpenoids, and minerals and are regarded as functional foods due to their ability to prevent disease and promote health. Regular fruit eating may also boost anti-aging, hypertension, and memory abilities. Anti-inflammatory, antibacterial, antifungal, and chemo-preventive qualities are among the additional advantages of fruits. Large-scale farming is used to produce a variety of items, including apples, oranges, plantains, bananas,

passion fruit, etc. (Chopra *et al.,* 2023). The production of different fruits around the world is 933.1 million metric tons in 2022-24 (Statista, 2024). Moreover, around, 15 to 60% of the fruit trash generated is made up of fruit peel waste (Ding *et al.,* 2023). Fruit peels are used in nutrient supplementation mainly because of their chemical makeup. Like banana pulp, banana peels are rich in organic material (lipids, fiber, carbohydrates, and protein) and are a major source of numerous bioactive substances with a variety of uses (Zaini *et al.,* 2022).

The United Nations Food and Agriculture Organization reports that the global fruit output in 2017 surpassed one billion tons, resulting in a significant amount of trash and by-products. Fruit waste is mostly responsible for the significant amount of processing waste biomasses produced by the manufacturing and consumption of food (Lucarini *et al.,* 2021). Fruit bruising, over-ripening, and damage sustained during storage and transportation are cited as some of the primary causes of food waste, and fruit wastes have been identified for their functional and/or nutritional qualities. Because of their potential health benefits for humans, bioactive substances with nutritional and nutraceutical uses have recently drawn a lot of attention from food industry by-products (Schieber *et al.,* 2017). In addition, bioactive goods made from fruit processing wastes highlight environmentally friendly methods for recovering important chemicals. The fruit waste's peels, pomace, and seed fractions make an excellent source of bioactive substances, such as phenolics, pectin, lipids, dietary fibers, etc. (Banerjee J *et al.,* 20170). The extraction of active chemicals from waste has just lately begun to move toward environmental certifications, as well as LCA (Life Cycle Assessment) and LCC (Life Cycle Cost) studies, which are also intended to lead to environmental product certifications. Numerous scientific endeavors are financed within the framework of national and European sustainability and innovation initiatives (Romani A *et al.,* 2020).

The banana fruit (*Musa acuminata*), which is a member of the Musaceae family, originated in Indo-China and Southeast Asia around 7000 years ago and is widely used to generate revenue in tropical regions of around the globe. Bananas are grown as a major crop in tropical regions, while China and India contribute more to their production. It is regarded as the most popular fruit in developed nations and as a necessary basic meal in many African nations (Joshi *et al.,* 2023). The global production of banana is around 135 million tons in 2023-2024 (FAOSTAT, 2024). Moreover, Pakistan is cultivating banana fruits on an area of 34,800 hectares and yielding around 305 thousand tons in 2023-24 (GOP, 2024). Moreover, the banana peel is a good source of dietary fiber, also rich in micronutrients *i.e.,* iron and zinc which are present in higher proportions in banana peels than in puree. Besides, food hygiene and safety can be enhanced through fermentation, which is widely regarded as a safe and acceptable storage technique. Because fermentation reduces phytic acid, food's dietary value and also enhance mineral digestibility (Oguntoyinbo *et al.,* 2020).

Furthermore, across more than 130 nations, both major and small farmers grow bananas. In certain economies, this fruit serves as a source of export income and is crucial to food security. The production and trade of bananas have significant socioeconomic value. In 2017, the world's banana production reached 113.92 million metric tons (MMT), a 15.35% increase from 2008. Gains in harvested area and yield were the main drivers of the increase in banana production throughout this time. In 2017, banana exports reached 23.18 MMT, a 26.67% increase over the same period. Approximately 50% of global banana exports in 2017 came from the top three exporters-Ecuador, the Philippines, and Costa Rica-while 35% came from the top three importers-the United States, Germany, and Russia (FAO, 2019).

According to research, banana peels can help avoid a number of illnesses, including diabetes, diverticulosis, diarrhea, irritable colon, colon cancer, and heart disorders (Oguntoyinbo *et al.,* 2020). Furthermore, terpenoids, alkaloids, flavonoids, tannins, and phlobatannins are among the different bioactive components found in banana peels. It has been utilized as an antiulcerogenic hypoglycemic, antidiarrheal, hypolipidemic, and antivenom-producing medicinal drug. Additionally, it is quite advantageous for preserving triglyceride levels. Due to its high carotenoid content (64 µg/g), banana peel can help prevent macular degeneration due to age, heart problems, diabetes, and a number of cancers. More phenolic content is found in banana waste than in avocado, pineapple, papaya, passion fruit, watermelon, and melon. The high carbon content of banana peel makes it an excellent absorbent for eliminating a variety of contaminants from raw water (Hashim *et al.,* 2023).

The pomegranate (*Punica granatum*) belongs to the Punicaceae family and is known for its medicinal fruit. It is a tiny tree or deciduous shrub with dunga-runga or perennial rootstock (Wanderley *et al.,* 2023). It was first grown as early as the fourth century in India. Later, Central Asian nations like Georgia, Afghanistan, and Iran began to cultivate it extensively. Since then, it has been brought to China, Myanmar, and Southeast Asian nations through trade, navigation, cultural exchange, and other means. Moreover, Pomegranates are often classified as either edible or ornamental. Edible pomegranates have large fruits, soft seeds, red blossoms, and medicinal use. Ornamental pomegranates have white blooms and small fruits. The edible portion of pomegranates, as a functional food, makes up roughly 57 to 85% of the entire fruit, of which 36 to 63% is fruit juice. Pomegranates have a mildly sour and sweet flavor thanks to advancements in modern farming techniques (Ge *et al.,* 2021).

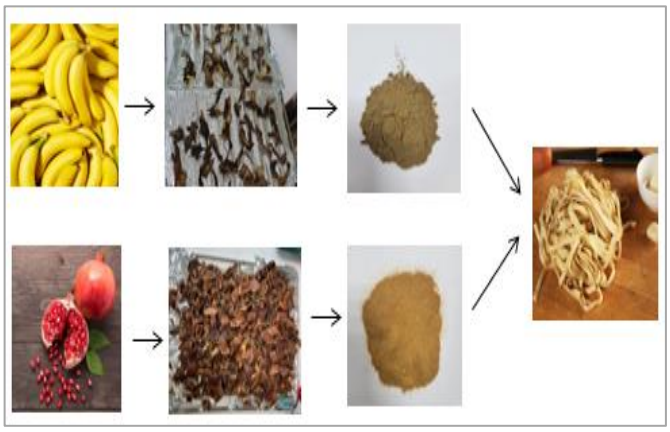
Pomegranate peel make up around 40% of the fruit weight and is a significant by-product of processing (Lacivita *et al.,* 2022). Global production of pomegranate and its byproducts reaches around 8.1. million tons annually (Ezeora *et al.,* 2024). According to a current estimate, around 1.9 million metric tons of pomegranate peels are produced worldwide on annual basis (Lacivita *et al.,* 2023). In Pakistan, around 57.8 thousand tons of pomegranates are produced annually, with a significant amount of waste generated by the processing industry (Saeed *et al.,* 2024). Pomegranate waste is a rich source of valuable constituents like minerals, and vitamins with anti-inflammatory, anti-cancer, and anti-microbial properties. Besides, ellagic acid in the peel is used in

skincare products to protect against UV rays and related disorders (Dewan *et al.,* 2024). Pomegranate peel is useful in a variety of products like chicken patties, cakes, muffins, biscuits, curd, fermented milk beverage, pasta, and edible oil (Singh *et al.,* 2023).

Pomegranate (*Punica granatum*) and banana (Musa spp.) fruits are consumed throughout the world and their processing generates large volumes of by-products (peels, seeds, pomace). The bioactive compounds in these by-products, which include polyphenols, flavonoids, dietary fiber and resistant starch, have been shown beneficial to gut health, reduce the risk of chronic diseases and possess antioxidant capacity. Yet, many of these essential compounds are underutilized or wasted, resulting in environmental problems and lost opportunities for augmenting the nutrition of food products (Sharma *et al.,* 2023; Martínez *et al.,* 2023).

Figure 1

Value-added product development from pomegranate and banana waste



The concentrations of phenolic compounds, flavonoids and tannins in pomegranate by products particularly the peel and seeds are high and have powerful antioxidant and antimicrobial activities (Kumar *et al.,* 2023). Due to their high dietary fiber content, pomegranate by-products are also good candidates to be used in pasta where they can enhance the product's nutritional value without changing to a great extent its basic characteristics. Banana by products such as peel and the over-ripe pulp are similarly enriched in resistant starch, essential minerals and bioactive compounds such as catechins and dopamine. Due to these properties, banana by-products represent an attractive candidate for functional food development (Rahman and Khatib, 2022).

Pre and Post-Harvest losses of Banana and Pomegranate

Pomegranate and other fruit losses and waste (wastage) can be caused by a variety of pre-harvest and postharvest reasons, such as pests, disease attacks, bruise damage, moisture loss, and mechanical damage, all of which lower profitability (Lufu *et al.,* 2020). Additionally, according to industry estimates in South Africa, sunburn, a pre-harvest skin condition, can occur often and cause growers to lose more than 30% of their produced fruit (Fadiji *et al.,* 2018). There is a dearth of quantifiable, scientifically based data on the extent of losses to direct the implementation of loss reduction programs, despite the causes of fruit waste in South Africa being identified. Fruits that do not satisfy quality standards because of the pre-harvest and postharvest conditions listed are deemed a loss and are either thrown away or sold for a nominal price as juice or animal feed Typically, pack house operations involve cleaning, sorting, grading, labeling, and packing fruit. The pack house, the final stage of fruit handling and quality control before storage, marketing, and distribution, is an important step in determining the extent and reasons for fruit postharvest loss, which are crucial details for developing loss reduction plans (Johnson *et al.,* 2018).

On-farm losses can vary from 15.3 to 20.1% of the crop that is harvested, mostly as a result of fruit quality problems that make it unsellable. Additionally, environmental elements like sunburn and cracking are responsible for roughly 43.9% of these losses (Opara *et al.,* 2021). The packhouse level experiences losses ranging from 6.74 to 7.69%, which translates into substantial financial losses of about ZAR 29.5 million (USD 1.75 million) per seaso. Chilling injuries can cause pomegranates to deteriorate and lose their marketability after harvest (Maghoumi *et al.,* 2023).

Furthermore, harvesting bananas at the full-mature (green) stage and hanging the bunches in a cool, shady area promotes flavor development for 7-14 days after harvest. Four unique stages of banana ripening are identified: (i) pre-climacteric, or "green life," stage; (ii) climacteric; (iii) ripe; and (iv) senescence. The commercial industry uses standard color charts to determine the banana's ripening stage, such as Stage 1 (dark green), Stage 2 (light green), Stage 3 (more green than yellow), Stage 4 (more yellow than green), Stage 5 (yellow with green tips), Stage 6 (yellow), and Stage 7 (yellow with brown freckles). Ripe fruit becomes soft and edible as a result of several physiological, biochemical, and organoleptic changes that occur during the ripening process (Evans *et al.,* 2020). Moreover, fungi and irregular weather patterns are typically the primary causes of disruptions to the normally year-round banana supply. A fungal disease that has the ability to disrupt banana production and trade as we know it, Fusarium Wilt Tropical Race 4 (TR4), is the biggest danger to banana crop worldwide. Disease remains the largest danger to banana output, especially Fusarium Wilt and Black Sigatoka (FAO, 2019).

Harvested fruit that is not transported and stored at the ideal temperature frequently experiences post-harvest losses. It is also shown that 20% of all picked bananas might end up as culls and be unsellable. It is noted that post-harvest losses for fruits and vegetables in developing nations are often far higher than in the US and can reach 50% for certain fresh fruits. Damaged, rotten, or damaged fruits that could cause microbial contamination of the entire bunch in the collection stations and bananas that were sorted too tiny for shipping could be the cause of these losses. Although low-temperature storage is one of the most crucial elements in regulating a banana's respiration rate, it also causes chilling damage, which leaves dark blotches on the peel (Evans *et al.,* 2020).

Pomegranate and Banana By-products: Composition and Potential

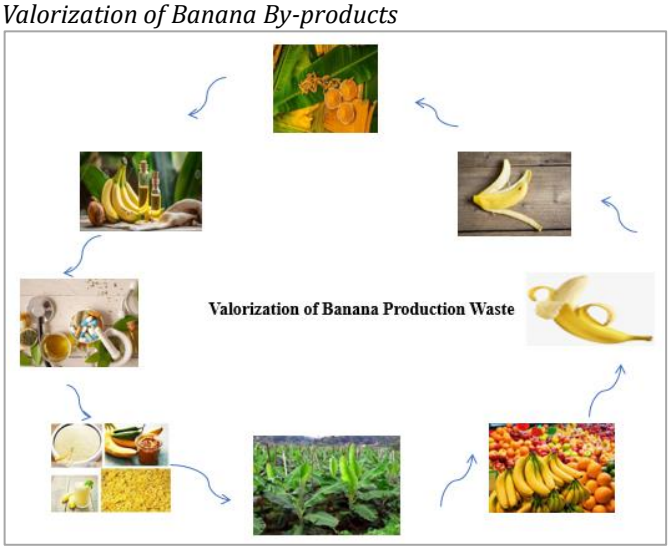
Pomegranate By-products

Byproducts of the seeds and peel of pomegranate (Punica granatum) are rich reservoirs of bioactive compounds that have generated interest for their nutritional and functional potential. Pomegranate peels (remnants) constitute about 30-40% weight of this fruit and are rich sources of polyphenolics, like ellagic acid, punicalagins and flavonoid (Kumar *et al.,* 2023). Strong antioxidant activities of these polyphenols are needed to enhance the life of living organisms by combating oxidative stress and preventing chronic diseases including cardiovascular disorders and cancer (Singh *et al.,* 2023). Furthermore, the peel can provide a large amount of dietary fiber, both soluble and insoluble, that helps increase gut health by maintaining microbial diversity and creating short chain fatty acids in the colon (Agarwal *et al.,* 2023).

Another valuable by product of pomegranate is pomegranate seeds discarded as waste, which is rich in punicic acid, a kind of omega 5 fatty acid, proteins and minerals like calcium, potassium and magnesium. These seeds also possess antioxidant properties, which make them a potential functional ingredient (Dey *et al.,* 2023). Furthermore, pomegranate peel and seed extracts possess antimicrobial properties, which allow their implementation in food preservation and widely meaning they can serve in food systems including pasta formulations (Bansal *et al.,* 2022).

Figure 2

Valorization of Banana By-products



Banana By-products

Another underutilized resource rich in bioactive compounds are banana (Musa spp.) by products which include peels and over ripe pulp. Banana peels make up about 35% of the weight of the fruit and possess resistant starch, dietary fiber and phenolic compounds like catechins, epicatechins and tannins (Rahman *et al.,* 2023). Banana peels recently received special attention due to their content of resistant starch, which smooth's overall glucose spreading and contributes to insulin sensitivity, making them very suitable for inclusion in diabetic – friendly food products (Martínez *et al.,* 2023).

Other than resistant starch, banana peels are abundant in minerals, such as potassium, magnesium and manganese, which are essential in many bones, muscles and enzymes functions (Sharma *et al.,* 2023). Besides, banana pulp, especially over ripe bananas, is rich in simple sugars, vitamins (vitamin C and B-complex) and bioactive compounds that increase its potential as a functional ingredient. Apart from the peel, both the pulp of banana also has prebiotic properties and help to promote the growth of healthy gut bacteria and support good digestive health. Incorporating these by products into food systems increases nutritional value while also increasing food sustainability by reducing food waste. The functional properties together with the capacity to enhance texture, flavor and shelf life render them as promising candidates for pasta formulations (Gowda *et al.,* 2022).

Drying Techniques for Banana Peel

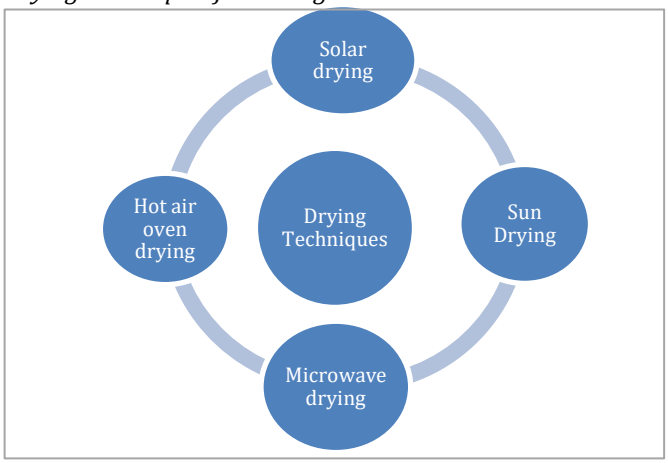
The drying techniques for banana peel pasta involve various methods that optimize moisture removal while preserving nutritional and bioactive properties. Key techniques include convective drying, rotary drying, and solar drying, each with distinct advantages and operational parameters (de Oliveria *et al.,* 2021). Connective drying uses an oven that circulates air at regulated temperatures, such as 60°C yields flour made from banana peels that has a moisture content of about 8.24% and can be stored without running the danger of microbiological growth and keeps the bioactive molecules at high levels, improving the nutritional value. Although, significantly more total phenolic chemicals (124.48 mg EAG/100g) are present in dried banana peel flour than in fresh peels. The flour is a useful ingredient for producing pasta because of its low water content (8.24%), which permits safe storage at room temperature (Silva *et al.,* 2020).

However, higher drying temperatures remove moisture more quickly, the end product's quality may suffer. According to studies, achieving the best outcomes requires balancing temperature and drying duration. On the other hand, although hot air-drying works well, other techniques like freeze-drying might retain more nutrients and tastes, though they might be more expensive for large-scale production (Faris *et al.,* 2020). Solar drying produces the fastest drying speeds when using active solar dryers, which use renewable solar energy and shows efficient moisture removal, with diffusivity rates that vary according on the drying technique (Agbede *et al.,* 2022).

The drying process can affect the functional properties as well as the physicochemical attributes of the products due to the heat involved in this process. The transformation of color, texture, permeability and shrinkage of bananas all occur when the bananas undergo the drying process. Different drying equipment and techniques will influence the nutrient and the physicochemical characteristics of the banana products. Given these challenges, the business industries are expected to implement suitable measures to minimize the defects and the nutritional and organoleptic losses that result during the drying process (Martinez *et al.,* 2024).

Figure 3

Drying Techniques for Pomegranate and Banana Peel Pasta



Drying Techniques for Pomegranate Peel Pasta

The process of drying has major effects on the health benefits of the pomegranate peel pasta and retention of its therapeutic properties. A range of drying methods including microwave and freeze drying, oven and sun drying and ultrasound-assisted drying can be used to preserve pomegranate peels, which reduces their storage volume while concentrating their nutritional content. In addition, numerous pieces of research have reviewed the edible part of pomegranate for potential uses as an antioxidant source, natural colorant, and in processing (Sarkar *et al.,* 2020).

Moreover, it is also possible to dry pomegranate peels in various methods, including sun drying, oven, microwave, and freezing. Because the sun drier relies on the sun, there is no need for additional equipment and electricity, and the pestil is colorful and transparent gloss after drying. Nevertheless, this approach has limitations with a prolonged drying time and the increased potential risk of microbial harm. Microwave and oven drying techniques have previously been tested to get around the limitations and unpredictability of sun drying (da Silva Simão *et al.,* 2020). Although, drying products at high temperatures has a detrimental effect on their nutritional value, aroma, and appearance. Therefore, in addition to improving the quality of the dried product, better drying techniques are required to maintain its nutritional value (Arslan *et al.,* 2024).

Currently, hot air drying is a financially viable method of food preservation since it can eliminate moisture, lower water activity, and maintain hygienic conditions, producing well-dried goods (Sarkar *et al.,* 2023). Drying can result in physical and chemical changes that harm plant tissues and decrease their capacity to rehydrate. These changes can include color changes, shifts in chemical composition, shrinkage, texture changes, and the loss of vital components, all of which can have an impact on the quality and acceptability of the finished product (Galib *et al.,* 2022) These adverse effects of drying include mechanical alterations and distorted form. Reducing the negative effects of drying on food quality requires careful consideration of process factors. Different food drying techniques each have their own benefits and drawbacks (Radojčin *et al.,* 2021). While the sun, oven, and microwave evaporate water, freeze drying includes sublimating the food after it has been frozen. Low temperatures and absence of residual water requirements help stop degradation and microbiological responses, which results in a high-quality end product. The antioxidant activity (77.86%) and total phenolic content (186.24 mg GAE/g DM) reached maximum levels with freeze drying (Sarkar *et al.,* 2022).

Microwave vacuum drying (MWVD) is an innovative method that associates the unique advantages of microwave and vacuum drying. Microwave volumetric heating is used for fast product drying and vacuum controls heating rate without sacrificing product quality attributes (Nongmaithem *et al.,* 2017). Another demonstrated and effective food preservation technique is vacuum assisted microwave drying, via a swell-drying procedure to improve the textural properties of food samples. Previously published research suggests that a lower pressure results in quicker water separation from the sample at relatively low temperatures, which can minimize the amount of chemical alteration that takes place in the dried sample (Mphahlele *et al.,* 2019).

Conventional air drying is the most often used method because of its advantages. Hydrothermal, thermal, microwave, radiofrequency, ultrasound, and others have been used as pre-treatments in overcoming or accelerating the timeframes of drying (Buvaneswaran *et al.,* 2022). The pre-treatments decrease the drying time while keeping antioxidant activity, color, minerals, and total phenol content. Therefore, a treatment such as ultrasonic (US) pre-treatment can alter the tissue structure of peels from pomegranate fruits, thus hastening the drying process with minimal nutrient loss (Malini *et al.,* 2024).

Effect of Processing Methods on Functional Ingredients

Processing techniques contribute significantly to the nutritional value and physicochemical properties of the primary raw ingredients such as pomegranate and banana. The quality, antioxidant potential, and bioactive retention capacity of these fruits are generally influenced by heat treatments and non-thermal techniques. Vitamins, antioxidants, and other sensitive compounds are usually lost through thermal treatment (Ma *et al.,* 2019). For example, polyphenols in pomegranate juice can be damaged by high temperature. Pasteurization of pomegranate juice showed lower phenolic content than non-thermal treatments indicated that heat treatments can certainly reduce microbial load while causing damage to the nutritional profile (Campos-Lozada *et al.,* 2024). High-pressure processing and other non-thermal methods improve the nutrient and antioxidant retention. Studies have demonstrated that HPP increases the antioxidant efficacy and total phenolic contents of pomegranate juice. Non-thermal methods improve the sensory and functional properties of fruits, which increase their consumer acceptance (Turan *et al.,* 2024). This conflict is highlighted by the fact that, while non-thermal methods may be able to sustain their nutritional value and they

may not always be as successful in ensuring food safety as traditional thermal methods (Tappi *et al.,* 2020).

Utilization of Banana and Pomegranate By-products into Pasta Making and their Impact on Physicochemical Properties

Pasta's physical attributes (color, nutritional profile, and water absorption capacity) are highly impacted when pomegranate and banana by-products are added. The quality and consumer acceptance of enriched pasta depends so much on these changes.

Utilization of Banana and Pomegranate By-products for Natural Color Extraction

A major consequence of pomegranate and banana by-products introduction in pasta composition is color change. Anthocyanins and other pigments that give red brown color to pasta products are found in high concentration in pomegranate peel. In short, this unique coloration can boost a product in the sense of attracting the attention of health aware consumers to natural and functional ingredients. The concentration and particle size of the pomegranate by product used determines the intensity of color, however (Kumar *et al.,* 2023). Likewise, banana peel, which is high in phenolic content, stains pasta a light brown or yellowish color. According to Rahman *et al.,* (2023) this may improve the visual appeal for particular aim crowds yet, he very nearly wild was excessive browning owing to phenolic oxidation may decrease consumer endorsement. Enzymatic browning inhibition or phenolic compounds encapsulation are strategies which can overcome this problem (Rahman *et al.,* 2023).

Water Absorption Properties of Banana and Pomegranate Waste By-products

Dietary fibers in pomegranate and banana byproducts have hydrophilic nature, thus increasing water absorption ability of pasta during both dough preparation as well as cooking. Greater water absorption enhanced the textural properties of pasta and led to firmer and less sticky pasta after cooking (Garg *et al.,* 2022). Nonetheless, excessive water absorption hinders the formation of desirable product attributes, *i.e.,* it presents the challenge of higher cooking loss or weaker pasta texture that would not necessarily meet consumer demands. The pomegranate by-products, rich in soluble fiber, increase the water holding capacity of the pasta, giving the overall structure of the pasts and preventing cooking losses. Moreover, banana by products also consist of resistant starch in the peel, which increases water retention during cooking and pasta stays well in shape and firmness. These properties must be optimized to find the appropriate balance between the desired functional benefits and acceptable consumer expectation for pasta texture and consistency (Sharma *et al.,* 2023).

Rheological Properties

Pasta dough rheology is fundamental to processing, its texture and final quality. With high fiber and also high bioactive content, the pomegranate and banana by products significantly influence the rheological behavior of pasta dough. The concentration, particle size and type of by product incorporated into the dough have a very significant effect on these effects (Ashwath *et al.,* 2022).

Impact of Banana and Pomegranate By-products on Dough Stability

Pomegranate and banana by-products modify the elasticity and extensibility of pasta dough, both key variables determining the machinability and quality of final product. Extensive insoluble fiber in the form of peel and seeds present in pomegranate by-products, weakens the gluten network by hindering gluten proteins of hydration and alignment (Agarwal *et al.,* 2023). So, this means the elasticity is going down, increased stiffness of the of the dough. Analogously, addition of banana peel, a source of resistant starch and dietary fiber, alters the extensibility of the dough by enhancing its deformation resistance (Sharma *et al.,* 2023). However, these changes may be moderated using particle size of the byproduct, in that finer particles are less likely to interfere with the gluten network and contribute to a smoother dough texture (Kumar *et al.,* 2023). The addition of by product at optimal level results in a workable dough grist while improving nutritional value. For example, it has been demonstrated that up to 10% of the peel leaves of pomegranate or banana maintain acceptable dough properties while not eroding the elasticity and extensibility of the dough. However, as the fiber interferes further, the dough becomes nearly impossible to handle, in which case, modifications to water or the introduction of hydrocolloids is necessary to counteract these effects (Martínez *et al.,* 2023).

Viscoelastic Properties

The inclusion of pomegranate and banana byproducts changes the viscoelastic properties of pasta dough, significantly altering their ability to show both solid like and liquid like behaviors. Interference of fiber and polyphenols from these by products with gluten formation results in a decrease in dough cohesiveness and elasticity (Dey *et al.,* 2023). The interactions between tannins and phenolic compounds from pomegranate byproducts, particularly, peel, and gluten network inhibit gluten cross linking and degrade the gluten network resulting lesser gluten network strength (Rahman *et al.,* 2023). It weakens the viscoelasticity of dough by lessening its ability to stretch or recover. Viscoelastic behavior also changes due to banana byproducts high resistant starch content. Differently from gluten proteins, resistant starch competes for the hydration during the dough mixing. This makes the water less available to gluten formation and increases dough hardness. An appropriate optimization of the mixing process and water-to-flour ratio decrease these effects and improves the hydration of gluten proteins and of fiber components (Sharma *et al.,* 2023).

Starch Gelatinization

The process of starch gelatinization is a critical step in pasta preparation, important to the texture and cooking quality characteristics of the final product. Banana by products resistant starch changes the gelatinization profile by raising the temperature for gelatinization and lowering the degree of starch swelling (Martínez, 2023). This ultimately translates into lower glycemic index for the

pasta which is favorable for those with their blood sugar levels to manage (Bansal *et al.,* 2022).

Table 1
Rheological properties of pasta dough influenced by pomegranate and banana by-products

Rheological Property	Effect	Key Factors	References
Dough Behavior	Elasticity decreases and stiffness increases due to insoluble fiber from pomegranate by-products. Extensibility altered by resistant starch and dietary fiber in banana by-product Finer particles improve dough texture and machinability	Fiber type and concentration Particle size Water-to-flour ratio Use of hydrocolloids	(Agarwal *et al.,* 2023; Sharma *et al.,* 2023; Kumar *et al.,* 2023; Martínez *et al.,* 2023)
Viscoelasticity	Gluten network weakened by fiber and polyphenols from pomegranate. Gluten cross-linking inhibited by tannins and phenolic compounds Resistant starch competes for hydration, increasing dough hardness	Polyphenol and tannin interference Hydration competition Optimization of water-to-flour ratio	(Dey *et al.,* 2023; Rahman *et al.,* 2023; Sharma *et al.,* 2023)
Starch Gelatinization	Resistant starch raises gelatinization temperature and reduces starch swelling Results in a lower glycemic index for pasta	Resistant starch concentration Gelatinization conditions Impact on cooking and nutritional quality	(Martínez *et al.,* 2023; Bansal *et al.,* 2022)

Sensorial Properties

Pasta sensory (taste, aroma, texture, and overall acceptability) are consumer preference critical determinants. The incorporation of pomegranate and banana by products into the final product however, brought with it peculiar attributes that either stimulate or depress the acceptance of the final product, depending on the concentration employed and the way in which the by product was processed (Baingana *et al.,* 2024).

Taste and Aroma Characteristics

Bioactive compounds in the pomegranate and banana by-products affect the taste and aroma of pomegranate and banana by-product enriched pasta. While pasta from pomegranate byproducts, especially pomegranate peel, is rich in polyphonies and tannin, which contribute slightly bitter and astringent tastes to the product. Although this bitterness turns off some consumers, it can also be used as a selling point of natural and health-promoting ingredients to health-conscious consumer (Agarwal *et al.,* 2023). Conversely, a mild sweetness is contributed to the pasta by banana byproducts, with natural sugar levels, in particular, when using pulp that is ripe. Based on this, pomegranate by products can create a bitterness that can be balanced out with the sweetness that is introduced in a product to make it more palatable. Furthermore, banana peel and pulp contain aromatic compounds which enhance the whole aroma of the pasta making the aroma fruity and attractive (Rahman *et al.,* 2023).

Impact of Fiber Content on the Textural Properties of Waste-derived Pasta

This paper investigates the influence of fiber on pasta texture and dough during both mixing and cooking; fiber alters the structural integrity of the dough and firmness of the cooked pasta product. Due to their high insoluble fiber content, pomegranate by products increased the firmness of the pasta, thereby making it significantly less sticky and less likely to overcook (Dey *et al.,* 2023). Similarly, banana by products improve the texture of pasta with relation to chewiness and avoiding of fragility during paste cooking (Sharma *et al.,* 2023). However, over incorporation of these byproducts can make the texture of the dough over coarse, since the fibers upset the smooth structure of the dough. The by-products' particle size is of critical importance in determining the pasta texture; finer particles producing a smoother pasta. Enriched pasta can be improved in terms of textural qualities by milling and sieving techniques to reduce particle size (Garg *et al.,* 2022).

Consumer Preferences and Market Potential of Waste By-product Pasta

Although the benefits of improved nutritional properties and antioxidant capacity of these by-products have attracted health-conscious consumers, taste, texture and color impact have to be dealt with so as to make them widely acceptable (Martínez *et al.,* 2023). Reportedly, the functional properties of the pasta can be improved with an optimal level of by product's incorporation, ranging from 5-15% without affecting the sensory appeal. However, beyond this range, the breading process will end up to getting undesirable characteristics, e.g., the pasta becomes bitter or coarse and the color changes making it an unmarketable commodity. A useful strategy is also provided by consumer education and targeted marketing, especially for functional or health-oriented products (Bansal *et al.,* 2022).

Cooking Properties

The cooking qualities of pomegranate pasta show significant gains in texture, nutritional value, and antioxidant capacity, especially when pomegranate fruit powder (PFP) or pomegranate seed powder (PSP) is added. These improvements are ascribed to the special qualities of pomegranates, which raise the pasta's overall quality. The inclusion of PFP from 4 to 12% greatly enhanced the dough's tensile and mixing qualities, leading to a more compact microstructure. Especially at 4 and 8% concentrations, PFP-infused noodles showed improved hardness, tensile strength, and resilience (Zhang *et al.,* 2023). Pomegranate pasta's higher radical scavenging activity demonstrated its improved antioxidant capabilities. A dose-dependent decrease in glucose release

was another effect of pomegranate addition, indicating possible advantages for glycemic control (Dib *et al.,* 2018). The ideal cooking periods and water absorption rates were maintained by pomegranate-enhanced pasta, guaranteeing the desired cooking qualities. (PSP-infused gluten-free pasta demonstrated enhanced cooking qualities and sensory qualities, suggesting pasta formulation versatility (Biernacka *et al.,* 2019).

However, a few of the variables that affect the cooking qualities of banana pasta are the kind of banana used, if protein fortification is added, and how the pasta is made. Banana pasta can be a good substitute for regular wheat pasta because research shows that it can have good cooking qualities and increase nutritious content. Green banana biomass (GBB) has been demonstrated to improve texture qualities like firmness and chewiness while lowering the ideal cooking time when added to pasta recipes (Keran *et al.,* 2022). Different green banana cultivars, like Pisang Tanduk and Pisang Nipah, produce pastas with different cooking qualities and levels of firmness; Pisang Berangan has the most firmness (Cheok *et al.,* 2018). Moreover, soy or egg white protein fortification greatly raises the protein level of banana pasta, bringing it up to par with semolina pasta. In addition to improving the nutritional profile, adding GBB raises the amount of resistant starch, which can reduce the pasta's glycemic index (Rachman *et al.,* 2019).

Cooking Loss

An important quality parameter for pasta is cooking loss, i.e. the quantity of solid material leached into the cooking water. Inclusion of pomegranate and banana by products increases cooking loss as they interfere with the gluten network. Protein complex named gluten from wheat flour serves as a necessity to form cohesive and elastic matrix that retains starch and other components in cooking (Kumar *et al.,* 2023). Pomegranate peel and seeds contain dietary fibers and polyphenols that can indirectly inhibit the gluten network formation through dilution of gluten forming proteins and by binding to it, primarily through hydrogen bond and through other mechanisms (Agarwal *et al.,* 2023). As a result, they are less cohesive in pasta structure and allow the leaching of solids into the cooking water (Agarwal *et al.,* 2023).

Furthermore, banana by products resistant starch and dietary fiber can pull in water during cooking, thereby disrupting the starch protein matrix. Disruption in this line increases solubilization of amylose and other starch fractions enhancing cooking loss (Sharma *et al.,* 2023). Nevertheless, when the incorporation levels of the pomegranate and banana byproducts don't exceed 10-15%, the studies show that cooking loss stays below 10% (Rahman *et al.,* 2023). Further mitigating cooking loss is possible through proper processing techniques, for example reducing the particle size or pre-treating the by-products (Rahman *et al.,* 2023).

Firmness Analysis of Banana and Pomegranate By-products

Another critical attribute of cooked pasta is how firm it is, which directly affects its texture and consumer satisfaction. The reinforcing behavior on the structural integrity of pasta is observed with the addition of dietary fibers and resistant starch from pomegranate and banana by-products. Fibers function as fillers in the gluten matrix and add mechanical resistance at deformation during cooking (Garg *et al.,* 2022). For instance, pasta fortified with banana peel shows great examples of this, as its high in resistant starch makes gelatinization take place at a slower rate, producing a firmer texture (Martínez *et al.,* 2023). The high concentration of by-product can, however, affect firmness negatively. A higher level of fibers disrupts the gluten network too much that it results in inadequate cohesiveness and hence softer cooked pasta accordingly (Kumar *et al.,* 2023). It has been shown that optimal levels of pasta textural enhancement generally occur at 5 to 15% of incorporation without compromising the overall textural quality. In addition, firmness can be improved by reducing the size of the particles and by blending with other functional ingredients to minimize fiber-induced disruption during processing (Kumar *et al.,* 2023).

Water Retention

Pasta's water retention capacity is highly dependent on hydrophilic dietary fibers in pomegranate and banana by products. Agarwal *et al.* (2023), observed that these fibers can attach water molecules in water and keep them during cooking which results in low water loss and help in better texture of the cooked product. The idea is that the soluble fiber in pomegranate peel holds water in the form of a gel which traps water. Apart from adding texture, it makes the pasta juicy and pleasant to eat; this would be noticeable especially in the lesser quality kinds of pasta. Because of their content of resistant starch and insoluble fibers, banana by products, especially the peel, show similar effect. Such components lead to a more robust matrix that extends to retain water during cooking, minimizing excessive drying of the pasta and providing the desired chewiness of the pasta. Yet, if too much of these by products are incorporated to pasta, pasta becomes over absorbing water and therefore, it becomes too soft or 'gummy'. The optimal product means achieving balance between water retention and other quality attributes (Sharma *et al.,* 2023).

Impact of Value-added Products on Food Security

Food security is significantly impacted by value-added products, especially when it comes to vitamin deficits and malnourishment. In addition to improving dietary intake and decreasing food waste, these products also give producers financial benefits (Singh *et al.,* 2024). Nutrient-dense value-added products, such those made from fruits and vegetables, are intended to compensate for deficits in important vitamins and minerals. The nutritional condition of undernourished children has been demonstrated to significantly improve with goods manufactured with partially defatted peanut cake flour, for example, improving their consumption of macro and micronutrients (Seema *et al.,* 2018).

Value-added product manufacturing can help farmers financially, especially in areas where food insecurity is a problem. This involves the growth of small-scale businesses that provide local communities more power. By reducing post-harvest losses and improving resource management, value addition has been associated with increased food security in Kenya (Khader *et al.,* 2017). It is

critical to control food loss in areas where food insecurity exists, as the consumable products can be converted into value-added products. Nutrient extraction and food preservation can be achieved through green leafy vegetable dehydration; such a technique, therefore, makes consumable products accessible to low-income people to acquire (Sing *et al.,* 2024).

Although, pomegranate and banana value-added products are crucial for treating deficiencies like anemia and malnutrition, though, because they may be transformed into nutrient-rich foods that enhance dietary intake (Kandylis *et al.,* 2020). Both fruits are rich in essential vitamins and minerals, such as iron and folic acid, which help prevent anemia. The high iron concentration of pomegranates aids in the synthesis of red blood cells, hence combating iron deficiency anemia. Taking it with iron-rich foods also enhances iron absorption due to its ascorbic acid concentration (Ahmad *et al.,* 2022).

Furthermore, the creation of banana flour enhanced with zinc and amino chelated iron provides a useful method of obtaining these essential minerals. Fortified banana flakes show potential in increasing children's intake of iron and folic acid, while stability during processing remains a problem (Ekafitri *et al.,* 2019). Value-added goods derived from these fruits can therefore provide consumers with convenient, healthful options while also assisting farmers in increasing their revenue and reducing the loss of food. Including these goods in diets can have a major positive impact on health outcomes and food security, especially for vulnerable groups (Singh *et al.,* 2024). Furthermore, the potential of banana and pomegranate products is encouraging, but in order to optimize their ability to fight anemia and malnutrition, issues such nutritional stability during processing and the requirement for a balanced nutrient intake must be resolved (Jagdale *et al.,* 2021).

Health and nutrition are becoming increasingly important as individuals look for quick, nutrient-dense eating options. For food processing to satisfy these requirements, it must be effective, economical, and long-lasting (Michel *et al.,* 2024). Using low-cost technologies to turn fruits into a variety of items will help the country's economy and farmers. Healthy customers value fruit-based products that are low in salt and high in potassium because they provide significant nutritional advantages (Singh *et al.,* 2024).

Role of Functional Ingredient By-products in Boosting Economy

Commercially, there is large-scale commercial potential especially in the food industry regarding the utilization of functional constituents that extracted from banana and pomegranate peel. The businesses can add values to commodities that would cater to the health-conscious dietary requirements while helping the environmental program by recycling such products (Cano-Lamadrid *et al.,* 2022). Pomegranate waste is an excellent alternative for the microwaves and ultrasound-assisted leaching of some antioxidants and dietary fiber. Various food items like liquids and confections can, therefore, become more nutritious using these extracts which retain their appearance of "clean label". Given the high consumer's acceptance levels and low extractive costs from products made by pomegranate peel, high profitability may lie ahead for foods manufacturers (Torres *et al.,* 2020).

Moreover, banana peels that are usually wasted can be utilized in the manufacture of functional foods as they are a source of nutrients and bioactive compounds. The increasing interest in health foods by consumers may thus create an opportunity for new products from banana waste, and business opportunities can arise from it. On the flip side, while the focus on recycling food waste is encouraging, barriers like consumer awareness and legal constraints might hold up these concepts from being widely implem ented. Nevertheless, much room exists for economical gr owth through ecological means (Pimentel *et al.,* 2022).

Challenges and Opportunities

However, incorporating pomegranate and banana by products into pasta has functional and nutritional benefits, but comes with great challenges. Key however is balancing the functional properties of these by products with sensory and processing requirements to successfully use them in pasta formulations (Rahman *et al.,* 2023).

Challenges

The machinability of dough is among the first of the major challenges in incorporation of pomegranate and banana byproducts. These by products have relatively high fiber content, therefore, disrupt the gluten network and results in reduced elasticity and extensibility of the dough. However, this stumbling block makes the development of smooth, cohesive texture, necessary for the extrusion and shaping of pasta, a challenging task (Kumar *et al.,* 2023). Moreover, phenolic compounds existing in pomegranate byproducts may interact with gluten proteins to deteriorate dough quality (Rahman *et al.,* 2023).

A second challenge is the management of the sensory properties of the enriched pasta. Pomegranate by-product has a low harshness along with acidity; it is so b ecause of having high polyphenol content while banana by-products have a mild sweetness that fails to go in harmony with traditionally accepted pasta flavors. Sensory changes have adversely affected consumer's acceptance, specifically among traditional consumers of pasta (Agarwal *et al.,* 2023). Incorporation at high levels, these by-products can reduce the elastic nature of the pasta, increase cooking loss, and make it mushy. To obtain the best combination of functional advantages and product quality, precise incorporation control and formulating refinement are essential (Garg *et al.,* 2022).

Opportunities

Despite the problems, incorporating pomegranate and banana by-products into pasta can result in innovation and sustainability. Some of the problems related to their use have been overcome with the development of food processing technology. Milling or micronizing by-products may improve dough elasticity and machinability by minimizing their disruptive action on the gluten network (Martínez *et al.,* 2023). Encapsulation of phenolic chemicals may protect sensory charateristics, structural strength. And quality of the products while minimizing

their interference with gluten interactions (Sharma *et al.,* 2023).

Blending of pomegranate and banana co-products with other functional ingredients, protein isolates or hydrocolloid s could be a favorable solution to develop synergies and improve both functional and sensory properties. For example, hydrocolloids can substitute for the low gluten strength by forming a secondary network strengthening the dough structure and increasing its elasticity and extensibility (Kumar *et al.,* 2023). Besides technological improvement, growing consumer demand for sustainable and health oriented products gives a strong market opportunity for adding pasta with pomegranate and banana by products. Accordingly, these products can be promoted as such high fiber, rich in antioxidants, contain productive functions for gut health, can decrease the risk of chronic diseases, and are environment friendly (reduces food and waste) (Rahman *et al.,* 2023).

Future Perspectives

The potential for use of pomegranate and banana by products in the pasta composition to enhance nutrition and sustainability has been remarkable. But several areas need yet to be explored and to be innovated in order to guarantee successful industrial application and market acceptance of these functional ingredients. Future research should aim to address the following key aspects.

Investigation of Incorporation Levels for Industrial Scalability

The foremost challenge in using pomegranate and banana by products in pasta is to find the best levels of incorporation in terms of functional benefits and acceptable sensory and processing properties. However, literature states that incorporation levels, in the range of 5 to 15%, are typically accepted, though values can also differ based on the specific by product, particle size, and pasta formulation (Kumar *et al.,* 2023). High levels of the incorporation may enhance nutritional and functional properties of the pasta but frequently cause undesirable alterations in texture, taste, and machinability. Future studies should use response surface methodology and other advanced modeling and optimization techniques to identify the combinations of ingredients and processing conditions that yield the greatest benefits and minimized drawbacks (Rahman *et al.,* 2023).

The standardization of processes for by product preparation, e.g. drying, milling and particle ″size reduction″ is required for industrial scalability. To guarantee product quality and performance of by products in pasta production, cost effective and scalable processing methods are necessary. Moreover, collaborations with food manufacturers will help transition laboratory scale findings to the kitchen scale for large scale production (Martínez *et al.,* 2023).

Synergistic Effects Between Pomegranate and Banana Byproducts: Exploration

The combination of banana and pomegranate by-products in pastas could provide synergistic benefits due to their complemented physiological and functional characteristics. Pomegranate by-products contain polyphenols and fiber, while banana byproducts contain resistant starch, prebiotic chemicals and minerals. Combining these by-products enriches the nutritional profile of pasta and adds medicinal value by providing antioxidant protection, glycemic control, and gut health (Kumar *et al.,* 2023; Rahman *et al.,* 2023). Further studies should focus on the synergistic interaction between the biologically active compounds from these by-products. The mixture of pomegranate polyphenols with resistant starch in bananas, for instance, would be additive or synergistic for antioxidant activity and gut health. Yet, in addition to examining by-products for their effects on the functional components of protein isolates or hydrocolloids, they could also be used as a means of enhancing the nutritional and sensory quality of pasta produced through enrichment (Martínez *et al.,* 2023). Besides enhancing the nutritional content of pasta, synergistic interactions could enhance pasta production and structural properties. For instance, the mixture of insoluble fiber from pomegranate with soluble fiber from banana

Consumer-Centric Product Development

However, the latter's success hinges on the consumer acceptance of pasta enriched with pomegranate and banana by products. The sensory evaluation studies, assessing consumer preferences for taste, texture, color, aroma, are future research. Consumer segmentation and preference mapping are advanced techniques to identify target markets and to develop product development for specific consumer groups (Agarwal *et al.,* 2023). Moreover, marketing campaigns focusing on health benefits of and sustainability of these enriched pasta products will attract consumers and stimulate demand. Clear and convincing labeling and storytelling about the environmental impact of using by-product utilization to reduce food waste can increase their perception and adoption (Garg *et al.,* 2022).

CONCLUSION

The incorporation of pomegranate and banana by products into pasta constitutes a promising innovation for the food industry that meets both nutritional and environmental needs. By turning these by products into pasta products, the nutritional profile of pasta increases (dietary fiber, antioxidant content and resistant starch) and a contribution to a sustainable food system via reducing waste is made. Nevertheless, also the addition of pomegranate and banana by products affects the physicochemical, rheological, sensorial and cooking properties of pasta. All of these changes, including increased cooking loss, changes in dough elasticity, and changes in sensory attributes must be carefully managed to maintain product quality and consumer acceptance. Maximum incorporation levels, particle size reduction and new processing techniques which include encapsulation and blending are critical to overcoming these problems. Further research needs to be done in order to fill key gaps: the long term stability of the bioactive compounds, the synergistic effects of combining the pomegranate and banana by products, and feasibility of scale up processing. Translation of these advancements into commercially viable products will require interdisciplinary collaboration among food scientists, nutritionists, and industry

stakeholders. Finally, pomegranate and banana by products could be functional agents in pasta due to their potential to satisfy the major quality demands and consumers' health concerns and an asset to their sustainability potential. The food industry can realize the full potential of these as yet underutilized resources, offering a new range of functional and sustainable food products through the use of innovative technologies and consumer centric approaches.

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