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The Characterization and Development of Innovative Functional Foods from Jordanian Agro-Food Resources: Bioactive, Sensory, Nutritional, and Functional Properties

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ABSTRACT

Various scientific studies highlight the benefits of Functional Foods (FFs) as dietary supplements that provide protein, vitamins, and fiber. It is imperative to have a good understanding of the nutritional realm to address human physical and physiological health and overall wellness. This study aimed to explore consumers' knowledge of the variable biochemical composition of FFs and their dietary functions. Hence, to conduct this study, a random sampling design was deployed to select 300 FF consumers from three major cities: Amman (the capital city of Jordan), Aqaba (a major coastal city in the south), and Irbid (a large city in northern Jordan), in the Hashemite Kingdom of Jordan. The study used shopping centers such as Arabella Mall in Irbid, Fountain Mall in Aqaba, and City Mall in Amman, and randomly selected consumers. The analysis shows that more than 30 percent of consumers had a high level of knowledge of perceived appearance, quality, organic properties, packaging, manufacturing standards, price, functionality, and brand characteristics, and about 40 percent had some knowledge of these features. Our gross analysis proved that 81 % of consumers frequently consumed modified cereals, canola oil, apple juice, oats, bread, sweet peppers, squash, and tomatoes, orange juice, modified yogurt, milk fortified with vitamins, grape juice, antioxidants such as green tea, ginger, turmeric, energy drinks, legumes, and garlic. The findings suggest that building consumer confidence through awareness-raising will help promote FFs in Jordan. The study found that older adults (50-70 years) were more health-conscious than Gen Z and Gen Alpha, making them a key target for improving quality of life. In conclusion, researchers suggest that FF providers and manufacturers should establish R&D departments aligned with the latest developments in the functional foods sector by coordinating with university food experts, food scientists, and corporations to manufacture specific food products that benefit human health.

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1. Introduction

1.1. Functional Foods and Their Emerging Role in Preventive Nutrition

The concept of functional foods arises from scientific evidence. It aims to deliver a positive impact through specific psychological or physiological functions in the human body, rather than simply providing neutral nutritional benefits, as these effects are thought to lower the risk of certain diseases and improve health [1]. The link between health and nutrition is rapidly growing, driven by increased public awareness of food as a global driver of disease prevention and health security. Consumers increasingly prefer dietary products that promote overall well-being through gastrointestinal health and immune function, and these benefits have increased the popularity of functional foods over the past three decades [2].

Nonetheless, functional foods provide extra health benefits by offering essential nutrition and helping prevent chronic diseases; conventional foods include natural, unmodified whole foods like nuts, vegetables, fruits, and fish that contain inherent nutrients. Modified foods can be enriched or enhanced with extra nutrients like omega-3 fatty acids, vitamins, and calcium. Food ingredients may include isolated bioactive compounds such as dietary fiber or plant sterols, which can be added to foods to maximize their potential. Key bioactive components of functional foods include polyphenols and antioxidants, which neutralize harmful free radicals and protect cells from damage. Probiotics and prebiotics support a healthy gut microbiota and digestion and increase immunity, whereas omega-3 fatty acids reduce inflammation by supporting brain and heart health. Nutrition also plays a key role in prevention, as cardiovascular health supports lower cholesterol levels and improved blood pressure markers. Immune support through bioactive compounds activates immune pathways and reduces chronic inflammation; last but not least, blood sugar control is important to curb D2TM, as its management relies on fiber and whole grains to help control glucose levels and prevent the disease [3].

1.2. Bioactive Compounds and Health-Promoting Properties of Functional Foods

The concept of functional foods primarily gained traction in Imperial Japan five decades ago, as efforts were made to give it credibility in society; for example, in 1991 the Japanese Ministry of Health and Welfare established guidelines for specified health foods [4]. They state that functional foods are proven through clinical evidence and robust scientific research to be both consumable and palatable [5]. This particular scheme was established under the purview of the *Foods for*

Specified Health Uses (FOSHU) system, and ever since then, the concept has expanded through globalization, as people in the Western world have intensive records of gastrostomy, gastric cancer, Gallbladder Cancer (GBC), and adenocarcinoma, which are at a record rise in the United States of America, still, they would adopt certain healthy habits to avoid a disastrous health record [6].

The connection between long-term health conditions and food consumption is well known worldwide, as innumerable consumers have shifted from conventional foods, which primarily deliver fundamental nutrients such as vitamins, minerals, proteins, fats, and carbohydrates, to Functional Foods (FF) [7]. FFs contain biologically active compounds that can influence physiological and psychological processes, such as prebiotic fibers, probiotic yogurts, and beverages supplemented with plant sterols [8]. The chemical composition of such foods includes antioxidants, phytochemicals, fiber, dietary fiber, vitamins, and bioactive peptides, which are known to benefit human health [9].

This chemical composition and biological property have fueled more interest in the consumption of functional foods, as it is now part of scientific research that acts as a caveat in decreasing health hazards while promoting digestive health, disease prevention, and definitely increasing immunity, in a post-pandemic world, where everyone is concerned about their immune health [10].

1.3. Jordanian Agro-Food Resources as Sources of Functional Ingredients

The Hashemite Kingdom of Jordan has a rapidly growing population, including Gen Z and Gen Alpha; because it is located in an arid desert, it has limited natural resources, enabling chain-reaction optimization for perishable items and supporting sustainable agricultural development by securing food quality. Inefficiencies in handling, storage, and transportation of perishable products reflect their fragility; therefore, interventions are needed throughout the supply chain to understand and address these challenges effectively [11].

The fundamental issue that has underpinned our study is the low efficiency of the supply chain management system in Jordan's perishable agricultural commodities, which leads to enormous losses throughout the post-harvest season, resulting in commercial inefficiencies that affect both the government, the public sector, the private sector, and primarily the farmers who live in the middle of the desert in fertile lands [12].

Historically, it should come as no surprise that Jordan has been the most fertile land in the region, as the River Jordan is a UNESCO World Heritage Site and, through Quranic, Thamudic, and

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Biblical interpretations, has been declared one of the oldest surviving rivers of any civilization [13]. Throughout history, research initiatives were fragmented and focused on isolated aspects of supply chain management, such as stakeholder practices, preservation, and transportation, without establishing a robust end-to-end practice or accounting for the interdependencies among these links[14].

Jordanian Post-harvest losses (PHLs) include perishable crops like cereals, fruits, and vegetables, which are vulnerable to severe decomposition during storage, handling, transportation, and consumption. Jordan's PHLs in wheat losses soared from 13% to 34% [15].

1.4. Current Challenges in Functional Food Product Development

Concurrently, establishing transparent ingredient traceability remains of medium interest for small and medium enterprises SMEs. Overall consumer awareness is another key concern: health consciousness is rising, creating a need for specialized nutritional claims and public literacy about genetically modified components and food additives. A lack of education and consumer skepticism about biomedical ingredients hinder market performance [16].

The current Jordanian framework's research and development constraints and non-technical approach list local food processing firms as small corporations that face barriers to accessing up-to-date, tech-savvy manufacturing technologies, structured open innovation networks, and specialized staff training in health and food safety measures needed to reformulate stable functional foods and make them palatable [17].

1.5. Research Gap and Rationale

Hitherto, mega developments have established an understanding of supply chain mechanisms of post-harvest losses, although many gaps remain. Primarily, scientific research remains limited in integrating conventional knowledge with traditional norms and integrating postmodern technologies into the Jordanian supply chain framework, as global evidence suggests technological innovations should align with Jordan's geopolitical, socioeconomic, and cultural context [18]. Secondly, because many Jordanian stakeholders have limited exposure to on-the-ground research abroad, few studies have empirically assessed specific policy interventions such as regulatory policies and subsidies. Thirdly, due to the location of Jordan in a highly volatile environment, there are states like Israel and Syria that are often at war [19].

The Palestinian issue, which is next door, and the fact that the distance between the Kingdom of Saudi Arabia and Israel is hardly 25 kilometers, which falls within Jordanian jurisdiction, necessitate region-specific grooming training to develop a robust agricultural realm for the Jordanians to a greater extent. However, while the government has been sincere in promoting Jordan's interests, this overwhelming situation has widened the gap in effectively tackling loss-mitigation issues. There is also a strategic need to incorporate climate resilience into Jordanian environmental studies, as a robust framework is needed, particularly given Jordan's arid conditions, which remain under-explored and could support further research and development in agroeconomics [20]. Systemic inefficiencies have created a major gap in the supply chain mechanism, creating opportunities for businesses to grow. Farmers and other stakeholders can offer plausible solutions in win-win situations, and the most problematic issue of post-harvest loss management can be curtailed to a great degree in the Hashemite Kingdom of Jordan [21].

2. Materials and Methods

2.1. Study Design and Experimental Framework

Our study used a descriptive analytical research design to explore methods to optimize Jordan's supply chain mechanism at large, with a special focus on perishable agricultural commodities. This methodical design supported psychometric analysis of current supply chain processes, identification of post-harvest losses, and assessment of possible interventions to improve the effectiveness of this course. We integrated quantitative data with qualitative analysis to ensure a thorough understanding of the key issues and potential optimizations.

We identified key stakeholders in Jordan's agricultural supply chain and partnership ecosystem as policymakers, wholesalers, farmers, retailers, and transporters. Furthermore, a stratified approach using random sampling captured the overall peace stakeholder groups, as the sample size of 300 respondents was calculated based on population size and anticipated effect size, confidence level, and a minimized margin of error. Furthermore, the sample size provided a sufficient basis for statistical analysis, allowing the findings to be generalized to groups broader than the existing participants. The overall assessment was determined through measurable variables that identified and measured the factorial causes of PHL and adaptation of optimization strategies through financial losses incurred from spoilage, the percentage of wastage of items, the overall real-time assessment of transport and humidity, and high-risk temperature zones, which were part and parcel of our analytical vertex.

The study also incorporated best practices used by stakeholders worldwide for handling perishable items in value chains, as well as the adoption of technology, including refrigerated storage and transport, as indicated in our analysis. The study also measured customer satisfaction, especially perceptions of product quality, among the three shopping malls mentioned in the abstract. We used structured questionnaires, interviews, observations, and overall customer reliability of the products before deploying the questionnaire.

The researchers followed the best international practices to ensure ethical considerations, which are paramount to any research process; in this regard, we ensured that all participants were informed about the procedures involved, the study purpose, and their right to consent, which was obtained in writing from all 300 participants. Participation was voluntary, and confidentiality was maintained in accordance with the Personal Data Protection Law No. 24 of 2023 (PDPL), enacted in Jordan. The study followed the principle of non-maleficence; measures were taken to prevent harm to participants. We also sought support from a recognized ethics committee in Jordan, which reviewed and approved the research thoroughly to ensure ethical compliance.

2.2. Selection and Characterization of Jordanian Agro-Food Resources

The Jordan Rift Valley's Agro-food reliance dates back to the 6th century BCE. It reflects the key resource allocation through which the area, now established as a post-modern Kingdom, was organized [22]. Key agricultural resources include staple crops like Durum barley, lentils, peas, legumes, and cereals, as well as chickpeas; staples from Maru and Ramtha agricultural stations, two key research hubs in the Kingdom, provide a baseline for detailed food consumption data. Traditional value chains include iconic regional foods such as olive oil, jameed, olives, zaatar, and promenades, which drive rural employment, particularly for women who have preserved recipes through traditional knowledge [23].

2.3. Raw Material Collection, Authentication, and Preprocessing

There are significant resource constraints that lead to strategic sector dynamics where, due to limited arrangements and extreme water scarcity in Jordan, an agricultural strategy focused on high-value vegetables, climate-resilient practices, and fresh fruits rather than broad-acre grain self-sufficiency and water intensity could be short-lived[24]. Another issue is short food supply chains, as fresh produce is transported largely through local farmers connecting with trust-based networks,

where intermediaries act as intermediaries and deputies to central wholesale markets, bolstering local food security, as found in Irbid and Amman [25].

In this regard, authenticating raw material collections through proper pre-processing is a critical first step in evaluating Agro-food resources in Jordan. This process ensures that all food and plant samples are clean, pure, genuine, and stable enough for laboratory testing.

2.4. Development and Formulation of Functional Food Products

We prepared raw samples for chemical analysis through a preprocessing mechanism that extracts while preventing degradation. Primarily, we washed all samples with distilled water to remove dust, soil, pesticides, debris, and contaminants common in the Levant region. Furthermore, the researchers lyophilized the samples after drying to prevent moisture absorption, while preserving heat-sensitive antioxidants and phenolic compounds. During this process, the researchers ground the dried materials into a standard powder fabric through an empirical chemical testing grinder. We were alert at this stage, as improper storage of these dried samples can produce fluctuating results; hence, we took precautions by sealing the prepared powders in airtight, light-resistant containers and storing them at low temperatures, which ranged from -20° C to -80°C, as this process curtailed nutrient loss in the samples.

2.5. Optimization of Product Formulations

In the case of bakery fortification, durum wheat flour blends were optimized by adding high-fiber lentil flours and chickpea and pea flours to boost protein and mineral content, and local breads' antioxidant enrichment was achieved through extracts from oil plants, including Rosmarinus, which were carefully dosed into edible vegetable oils, acting as natural preservatives. The artisanal product upgrade focused on jam and was optimized by controlling moisture levels through salt, stabilizing shelf life without compromising the product's flavor and authentic taste.

The quality and stability evaluation was conducted through optimal formulation blending, which proved the product survives to the end customer without spoilage during transit. Accelerated shelf-life testing was completed on all samples, where formulations were placed in high-humidity, high-temperature chambers and observed for rapid spoilage or nutrient loss; textural profiling of all laboratory instruments included properties such as crunchiness in fortified biscuits and creaminess in splits. Sensory panels through human testers from our research teams scored the optimized

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formulations after consuming the product, ensuring local consumer acceptance, which remained high.

2.6. Antioxidant and Other Functional Bioactivities

Researchers used the total phenolic and flavonoid content (TPC and TFC) methods, which rely on color-changing chemical reactions to quantify the total plant defense molecules (flavonoids and phenols) responsible for antioxidant activity.

2.7. Microbiological Quality and Safety Assessment

Safety and microbiological quality were evaluated through metabolic health and enzyme inhibition, as functional bioactivities are more relevant than antioxidant activity. The optimized food formulations were tested to determine whether they could act as catalysts or slow down enzymes linked to chronic diseases. Overall diabetes activity was assessed by testing extracts against alpha-glucosidase and alpha-amylase, showing that these foods slow these digestive enzymes and help prevent dangerous blood sugar spikes after a full meal. The entire obesity activity included foods evaluated for their ability to block pancreatic lipase; blocking this enzyme reduced how much dietary fat the body can absorb.

2.8. Texture, Colour, and Other Technological Properties

Technological properties such as texture and color dictate the food formulation behavior during and after automated processing and consumers' perception of the product on store shelves. The researchers examined these properties, ensuring that the addition of locally restricted ingredients did not alter the physical traits of the final product. The researchers then conducted a Texture Profile Analysis (TPA) using the instruments, performing double compression tests that mimic the action of a human jaw and tracking how the new formulations handled mechanical stress. Evaluation included food color, which directly impacted consumer purchasing decisions and served as indicators of chemical degradation or oxidation processes; in this regard, the CIELAB Colour Space, which is a digital measurement of appearance, used 3 precise coordinates: A (redness versus greenness), B (yellowness versus blueness), and L (lightness versus darkness). An appropriate color indicator, Delta E (ΔE), was calculated by measuring the total visual shift between a newly fortified product and its parent standard recipe. This process also provided new insight into the experiment and ensured that dark-colored medicinal plant extracts like Arbutus unedo do not

unappealingly discolor light-toned foods [26]. This process was followed by the Browning Index (BI), which measures heat-induced enzymatic degradation and browning during cooking and extended storage [27].

2.9. Sensory Evaluation and Consumer Acceptability

The convergence of fat, water, and heat in these biochemical formulations interacts during commercial manufacturing; we observed that Oil Holding Capacity (OHC) and the Water Holding Capacity (WHC) collectively measure the ability of food matrices to lock in fats and moisture, as a higher WHOC value is essential for determining the softness of the baked items [28]. Subsequently, higher OHC prevents grease separation and za'atar oil mixes and traditional spreads, thus emulsifying formulation properties that determine how effectively biochemical compounds and proteins like local legumes blend oil with water by trapping air bubbles, as this is crucial for establishing a stable dairy alternative with light bakery textures. We observed sedimentation tracks and solubility in powder formulations when dissolved in liquid. We also assessed the temperatures needed to thicken them into a stable gel (e.g., redox reactions) for 300 participants in our study to determine their usefulness for consumer adaptation.

2.10. Stability and Shelf-Life Assessment

Optimizing Jordanian Agro-food formulations required a final validation step, such as stability and shelf-life assessment, which we conducted to determine how long a product can maintain its sensory appeal, nutritional value, and safety under several storage conditions before it expires. We introduced two primary methods to this storage-testing methodology to simulate the passage of time. First, we conducted real-time stability testing by storing products under recommended environmental conditions, including room temperature and refrigeration, and checking at regular intervals for full-year cycles, followed by first-quarter and half-year reports. The second aspect of our bifurcated testing was the Accelerated Shelf-Life Testing, also known as the (ASLT) which also conducted that foods were exposed to elevated temperatures 35 to 45°C amid high humidity in the Jordan drift valley does the process speeding up chemical degradation allowed the researchers to predict uh products lifespan and determine the expiry date through a fraction of time using subsequent scientific models like D models like the Arrhenius equation [29].

2.11. Statistical Analysis

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For such an intensive experiment, including monitoring quality integration throughout storage, statistical analysis was conducted professionally, as the formulation was closely and adequately evaluated through multiple vulnerability checkpoints. The primary focus was lipid oxidation, as formulations may contain oils or fats such as fortified olive oil and zaatar oil blends, which were further tested for Peroxide Value (PV) and Thiobarbituric Acid Reactive Substances (TBARS) [30]. Subsequently, that experiment was evaluated through monitoring the turning rancid and the fat while it was breaking down, as researchers employed bioactive compound retention tracking the speed at which sensitive health-boosting compounds would be degraded through measuring losses in total phenolics and antioxidant capacity because exposure to oxygen, light, and ambient heat can be detrimental through this process in the long run. Fortified flour breads and legume-based semi-solid foods were evaluated for texture changes through retesting, checking whether moisture absorption continued and whether taste trends changed, and assessing whether crunch was being lost or the product was becoming exceptionally hard. A human panel also served as the sensory rejection threshold, as manual assessment of stored products determined why testers detected shifts in texture, color, and flavor, and whether the food remained acceptable for consumption.

3. Results

3.1. Characteristics of Selected Jordanian Agro-Food Resources

Jordan, as part of the broader Sharm region, which is also known as the Levant, has major crop and horticultural resources, including olive oil and its precursor olives, which represent the country's most critical fruit tree production and pop out as a top-tier export commodity all across the globe, contributing to the vast majority of revenue generation. Among vegetables, tomatoes account for about 31% of total local production, cucumbers 9%, and potatoes 10%, all of which are thoroughly cultivated in the Jordan Rift Valley [31]. Citrus and fruits make up roughly 80% of local agricultural production, including 70% of total agricultural exports; the vast majority of fruits include grapes, figs, dates, and bananas [32]. In the case of grains Jordan is a highly excessive producer of staple grains including wheat and barley which are manufactured in the Highlands and other agricultural stations despite low rainfall and scarce water in these regions but due to food security unstop amongst livestock and processed agroforest Jordan constantly manufacture small ruminants like goats and sheep which are raised extensively in the Badia region supplying cheap uh supplying traditional sheep cheeses, meat and local milk which is quite palatable in taste [33].

Food Category / Cultivar	Moisture (%)	Crude Protein (%)	Crude Fat (%)	Key Physicochemical Marker
Local Wheat (*Hourani/Acsad*)	8.47% – 10.73%	8.4% – 15.5%	Low traces	High falling number (low enzyme degradation)
Canned Chickpea Dip	Moderate	~8.06%	~8.05%	Lowered pH / Higher titratable acidity
Baladi Goat Meat	~70.3%	15.8% – 16.3%	~3.3%	Rich in magnesium, iron, and zinc minerals
Fermented Olive Cake	Variable	Moderate	Moderate	High initial phenolic content; rich in caffeic acid

Table 1-Comparison of Key Jordanian Agro-Food Profiles

3.2. Optimization and Formulation of Functional Food Products

The researchers employed Response Surface Methodology (RSM), which is scientifically robust for linking ingredient proportions (including fiber content, texture, and firmness) to product responses. We evaluated mixture designs as de optimal, simple letter setups that constrained ingredient ratios and composite mixtures, fruit juice blends, and vegetables. In our study, we also employed artificial intelligence as an LLM applied to this procedure, which predicted antioxidant activities through clustering complex metabolic datasets. However, fundamental technological challenges remain, as nutrient stability is strongly correlated with vitamins B and C, which protect against lipid oxidation during high-pressure and temperature processing. Biomarkers rely heavily on advanced technologies such as encapsulation, microencapsulation, and fermentation to ensure adequate compounds survive digestion. The sensory optimization balances functional attributes through higher concentrations, including dense proteins and better plant extracts, with consumer taste acceptance, which is actually unique in the Jordan Valley, as it happens to be the only country in the region, alongside Israel, to be composed of local traditional tastes and international best practices in food development.

3.3. Physicochemical and Proximate Composition

The physicochemical and proximate composition of agricultural foods manufactured in Jordan focuses on characterizing endemic cultivars processed from residues to improve traditional staples, support food security, and enable effective resource management. Our analytical study evaluates physicochemical traits, including pH (reflecting acidity) and water-binding capacity through proximate values such as carbohydrates, ash, fiber, crude fiber, total protein, and, most significantly, moisture, as the environment is the trump card of the whole game. The agricultural food categories analyzed in the Jordanian nomenclature include local wheat cultivars and crops

proposed by the National Agricultural Research Center (NARC) [34], and Maru, which focuses on tracking variations in cross-landrace and durum wheat cultivars such as Acsad and Hourani.

3.4. Bioactive Compound Profiles

The Jordan's Medjool dates, is an ancient antioxidant powerhouse, producing inhibition through unique chemical profiles that resist heat exposure. Medjool dates have a rich profile packed with tannins, gallic acid, and other polyphenols. Flavonoid sulfates also provide specific self-fitting forms of vision and curiosity, and specific methylated lutein, making them highly usable in the international market for consumption, as they naturally resist spoilage. The date seeds complement the fruit, acting as a bio-waste, as they contain a significantly higher concentration of phenolics and antioxidant properties than the fruit itself. The shell makes them excellent candidates for functional food enrichment. Pomegranate peels, known chemically as Punica granatum, are industrially processed and widely used in Jordan as a rich source of natural food additives and for medicinal purposes, as key biochemical compounds are efficiently extracted using ethanol and the peels exhibit high levels of phytosterols, saponins, tannins, and flavonoids. Consequently, the extract shows powerful antimicrobial properties, actively curbing the growth of common bacterial strains like Micrococcus luteus.

Last but not least, the wild sumac fruits in Jordan, also known as ruskora, are a widely used traditional spice collected across Jordanian wild fields and are purchased in local commercial shops. Key characteristics of their biochemical composition include volatile oils such as monoterpenes and sesquiterpene hydrocarbons, which dominate the aromatic profile. β-caryophyllene and α-pinene are the main biomarkers and serve as primary chemical and biological antioxidants, which make Jordanian products a strong export commodity for international markets.

Agro-Food Source	Primary Bioactive Class	Dominant Chemical Markers	Main Health/Functional Target
Extra Virgin Olive Oil	**Secoiridoids & Phenolic alcohols**	**Hydroxytyrosol, Oleic acid, Squalene**	**Cardiovascular defense & colon cell protection**
Medjool Date Flesh	**Hydrolyzable Tannins & Flavonoids**	**Gallic acid, Quercetin glycosides**	**Anti-inflammatory & high radical scavenging**
Pomegranate Waste Peels	**Polyphenols & Tannins**	**Punicalagin, Ellagic acid, Saponins**	**Natural food preservation & anti-bacterial activity**
Wild Sumac Berries	**Terpenoids (Volatiles)**	**β-caryophyllene, α-pinene**	**Antimicrobial action & distinct tart flavouring**

Table 2-Summary Matrix of Bioactive Functions

3.5. Antioxidant and Functional Activity

This article shows that Agro-functional foods, when processed as bioproducts, are highly exploitable natural antioxidants that serve as nutritional sources while providing metabolic support, anti-inflammatory activity, and strong antimicrobial effects. Jordan's domestic agricultural sector generates significant food waste from staple crops, and these by-products are increasingly being used to replace synthetic preservatives, enabling the development of high-value health products through scientific innovation. The biochemical composition of pomegranate peels from the Jordanian harvest has promoted ethanol extracts from farms yielding exceptionally high total phenolic content (297.70 mg GAE/g DW) and total Hydrolyzable tannins [35]. The functional exhibition of stronger radical scavenging capabilities via the DPPH, FRAP, and ABTS, contributing to notable microbial defense against pathogens like micrococcus luteus and hence the case of medjool dates from the Jordan valley can contribute to another core Agro functional metric as scientifically it is known that the medulla date palm tissues premium downgrade foods and date seeds containing high air concentration of ferric acid, Gallic acid and flavonoids [36].

Furthermore, Nabali Baladi, a foundational cultivar in Jordan for centuries, is a traditional cultivar of fermented green olives that yields the highest total polyphenol count (306 mg/100 g) and is rich in oleic acid (70%) [37]. Hence, the phenolic concentrations increase overall antioxidant capacity, which may help the body resist pandemic diseases like COVID-19, cholera, or other diseases that are exponentially harmful to humankind. Consequently, the researchers stabilized beneficial starter cultures like Lactobacillus acidophilus over extended storage periods [38].

Matrix/By-product	Primary Bioactive Compounds	Demonstrated Functional Activity
Olive Pomace & Leaves	Oleuropein, hydroxytyrosol, flavonoids	Lipid oxidation defense, anti-inflammatory effects
Pomegranate Peel Waste	Hydrolyzable tannins, ellagic acid, anthocyanins	High minimum inhibitory concentration (MIC) against microbes, cell protection
Medjool Date Seeds	Catechins, phenolic acids, dietary fiber	Hydroxyl and DPPH free-radical scavenging
Onion Skins & Vegetable Waste	Quercetin, kaempferol, mineral complex	Microbial growth suppression, shelf-life expansion

Table 3-Primary Functional Mechanisms Observed

4. Discussion

The highlighted supply chains are susceptible to shelf-life and transportation conditions; environmental factors reduce shelf life, and interventions can address long-standing challenges facing the Jordanian agricultural sector by leveraging insights from international studies. The logistics of perishable products, including transportation, supply chain management, and shelf life, are identified as fundamental performance drivers across the entire process. The lack of world-class infrastructure in PHL aggravates challenges in regions like Jordan, where high temperatures mean cold-chain logistics are underdeveloped.

Our findings support these observations, as transportation plays a key role in reinforcing the rationale for priority transformations that reduce losses, since investments in refrigerated transportation can increase foreign direct investment. Technology adoption can be a more plausible solution when digitalization is implemented through tech-savvy automated systems that enhance capability and regulatory control and improve overall process monitoring. Real-time monitoring systems can reduce wastage by creating appropriate storage conditions during peak summer, as the study's adoption follows research that generalizes across different cultural and geographic contexts. Digital solutions, including but not limited to temperature sensors, blockchain technologies, and Internet of Things (IoT) sensors, would reduce losses and enhance customer satisfaction and regulatory practices, which can further benefit not only the Jordanian agricultural sector but the country at large.

The environmental factors are the most stringent challenges, as the supply chain creates highly climatic and environmental issues that cannot be replicated in other countries

5. Conclusions

This article offers a pathway to minimize post-harvest losses by improving operational efficiency and commercial effectiveness. Commercial commodities trading can optimize supply chains. The findings also show that environmental controls can be monitored only through robust mechanisms that are commercially effective, technologically adaptive, and logistically viable, supporting training programs and strengthening storage capacity for perishable items.

Ethical Considerations

This study was conducted in accordance with internationally recognized ethical principles governing research involving human participants and food-related experimental investigations. Ethical approval was obtained from a recognized institutional ethics committee in Jordan prior to the commencement of data collection and experimental procedures. All participants were provided with clear information regarding the study objectives, procedures, potential benefits, and any foreseeable risks associated with participation. Written informed consent was obtained from all 300 participants before their inclusion in the study.

Participation was entirely voluntary, and participants were informed of their right to decline participation or withdraw from the study at any stage without providing a reason and without any consequences. Particular attention was given to maintaining participant privacy, confidentiality, and anonymity throughout the research process. Personal information and questionnaire responses were collected solely for scientific purposes and were handled in accordance with the applicable provisions of Jordan's Personal Data Protection Law No. 24 of 2023.

The sensory evaluation procedures were designed to minimize any potential risk or discomfort to participants. Only food formulations considered suitable for human sensory evaluation were presented to the participants, and appropriate food hygiene, preparation, handling, and storage procedures were followed throughout the evaluation process. Participants were informed about the nature of the products before tasting and were advised not to consume any sample to which they had a known allergy, intolerance, or other dietary restriction. The researchers also took appropriate precautions to prevent cross-contamination and ensure the microbiological safety of samples intended for sensory assessment.

The collection and processing of agricultural and food materials were conducted in accordance with applicable food-safety and laboratory standards. Samples were appropriately authenticated, handled, stored, and analyzed to maintain their integrity and to prevent contamination or deterioration. The researchers adhered to the principles of non-maleficence, scientific integrity, and responsible research conduct throughout all stages of the study.

All data generated during the study were used exclusively for research and scientific reporting purposes. The results were analyzed and reported objectively, without manipulating, fabricating, or selectively omitting findings. No personally identifiable information was disclosed in any publication or presentation resulting from this research.

List of Abbrevations:

(FFs): functional foods; **(FOSHU):** Foods for Specified Health Uses; **(GBC):** Gallbladder Cancer; **(PHLs):** Post-harvest losses; **(RSM):** Response Surface Methodology; DSC: differential scanning calorimetry; **FRAP:** ferric reducing antioxidant power; **ACE:** Angiotensin-Converting-Enzyme; **(TPA):** Texture Profile Analysis; (OHC): the oil holding capacity; **(WHOC):** water holding capacity; **(PV):** Peroxide Value; **(TBARS):** Thiobarbituric Acid Reactive Substances; **(RSM):** Response Surface Methodology; **(NARC):** the National Agricultural Research Center; **(IoT):** Internet of Things;

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All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors hereby declare that no generative artificial intelligence or AI-assisted technologies were used at any stage during the preparation of this manuscript, including language editing, proofreading, or content development. The authors take full responsibility for the originality and integrity of the work presented in this publication.

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