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REVIEW PAPER

APPLE JUICE AS A FUNCTIONAL BEVERAGE: TREND IN EMERGING TECHNOLOGIES AND CONSUMER DEMAND

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Abstract
Consumer preference for apple juice is due to cultural, regional, nutritional, functional, therapeutic and social factors. Some of the existing research in this area of the food industry is found in this study. The position of apple juice from various perspectives and the international classification of juices are therefore presented. The chapter entitled Apple as a raw material in the juice industry highlights apple varieties from the Dîmbovița Valley, Romania. Classic and emerging technologies in the juice industry show that pulsed electric fields, high pressure processing, enzymatic treatment, tangential filtration and classic techniques, suitable for continuous or discontinuous production flow can be used regardless of the addition. The advanced and classical methods of juice quality investigation are reviewed and their selection helps highlight the influence of functional additives. The variants of the presented drink combinations based on apple juice are: the combination with beetroot; added calcium, vitamin C and iron; fruit addition; tea polyphenols; smoothies with complex structure; addition of bee products. They can be the basis for future research of your own. The market outlook shows an increase in the consumer interest in natural functional beverages. The role of the variety selection, the juice extraction techniques, the analysis and the control methods in obtaining apple juice drinks with competitive and functional potential is thus highlighted. From an economic point of view, apple juice is an advantageous choice for Romania

Keywords: juice, apple varieties, technology, functional beverages, physicochemical analysis

Introduction

Apple juice is a liquid obtained by pressing or squeezing fresh apples, without fermentation, with or without the addition of water, sugar, or citric acid, depending on the type of product. It can be consumed as such or used as a base for other

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beverages and food products. In its natural form, apple juice contains no additives or preservatives and retains the aroma and nutrients of the fresh fruit (Vasile & Popescu, 2018). Apples (*Malus domestica*) are among the most consumed fruits in the world and originate from deciduous fruit tree species belonging to the *Rosaceae* family. These fruits are an important source of vitamins, minerals, fibers, antioxidants, and polyphenols.

Due to their nutritional value, apples support digestive system health and may help prevent chronic diseases such as diabetes, hypertension, or arteriosclerosis (Way *et al*., 2023). Although traditional consumption involved eating raw apples, modern dietary trends favor their transformation into various products such as juices, jams, or dairy derivatives. Over 90% of the processed apple quantity is used for producing juices and beverages. The raw material intended for apple juice production is largely locally sourced and meets high quality standards, making these juices an excellent choice for the production of fruit-based beverages (Marica *et al*., 2022).

The apple juice industry is currently experiencing a convergence of consumer nutritional demands, a pressure for traceability and sustainability, and advancements in analytical methods. Recent research on raw materials emphasizes the choice of cultivar, the degree of ripening, and the post-harvest practices, factors that shape the phytochemical matrix (polyphenols, organic acids, pectin) and, implicitly, the sensory profile, the stability, and the nutritional value of the juice. In the case of beverages based on cloudy apple juice, scientific interest focuses on maintaining the colloidal phase (the "cloud") and optimizing functional additives from vitamin C and soluble fibers to botanical extracts so that the nutritional benefits are enhanced without compromising key aspects such as turbidity, color, viscosity, and aroma (Kim *et al*., 2021).

A central pillar of the literature is the evaluation of the quality and the authenticity. In addition to the traditional indicators (°Brix, titratable acidity, pH), the modern methods include high-performance liquid chromatography for profiling polyphenols and sugars, ultraviolet-visible spectroscopy(UV-Vis), Fourier transform infrared spectroscopy (FT-IR), and Near Infrared (NIR) spectrometries for rapid screening, as well as Liquid chromatography and mass spectroscopy -Gas chromatography-mass spectroscopy (LC-MS/GC-MS) and Nuclear Magnetic Resonance (NMR) for the metabolic fingerprinting and detection of non-compliant ingredients/additives (Rydzak *et al*., 2020).

The characterization of the cloudy juices relies on turbidimetry, particle size analysis, rheology, and microscopy for describing cloud stability, while tools such as colorimetry, electronic nose technology, and descriptive sensory analysis complete the picture of perceived quality (Dasenaki & Thomaidis, 2019). At the same time, safety concerns—from patulin control to monitoring residues and oxidation are integrated into risk-based control schemes using chemical and microbiological indicators (Duan *et al*., 2023). In this context, the present study examines the sustainable chain of functional apple juices (Figure 1).

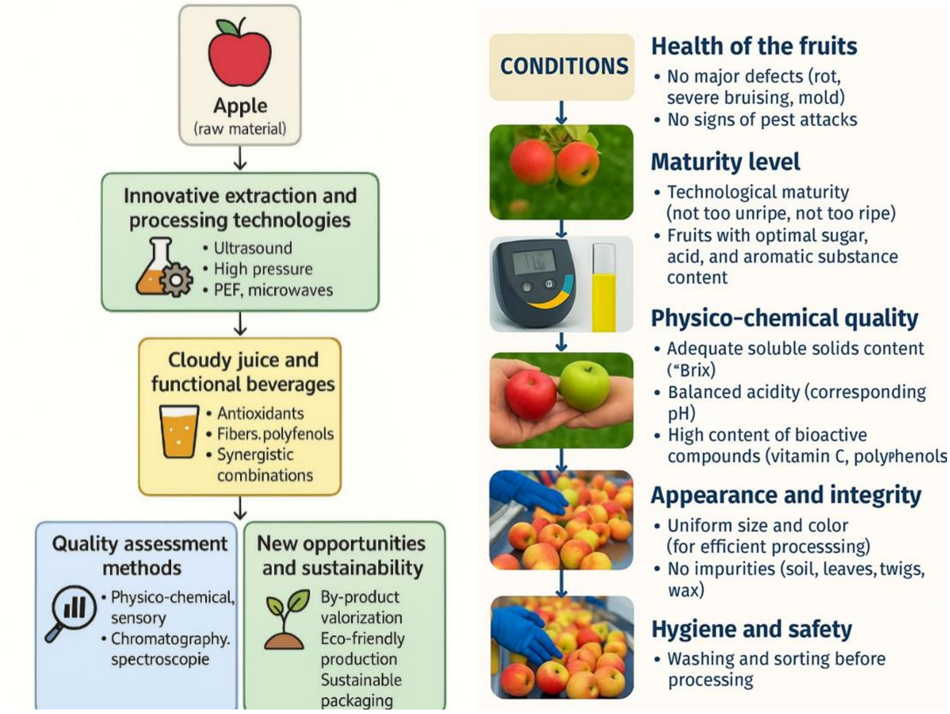

Figure 1. The technological chain of functional apple juices(left**),** conditions that apples must meet in order to be processed into juice(right).

Fruit juices (Table 1) constitute a valuable source of bioactive compounds for the human body; however, technological processing and storage can significantly reduce the content of these substances (Gomez-Gaete *et al*., 2024). In this context, consumer preferences have increasingly shifted toward freshly squeezed juices to maximize the intake of beneficial nutrients. The study aims to synthesize and analyze the literature regarding the raw materials used in apple juice production, with a focus on the particularities of apples grown in the Dâmbovița region, the characteristics of cloudy juice, and beverages obtained through functional ingredients. It also aims to evaluate and discuss the nutritional and functional implications of the chosen nutrient and juice formulation, in relation to current trends in the field of functional beverages. Another objective is to review and compare the qualitative investigation methods used to assess the composition, authenticity, and stability of the products. The final goal is to outline an integrated framework based on the specialized literature to guide raw material selection, product design, and quality control, in line with consumer expectations and current industry standards.

Table 1. Classification of juices (according to the EU Fruit Juice Directive, 2015).

Variety	Main characteristics	References
Classification criteria according to composition		
Fruit juice	Fruit juice is defined as a "fermentable but unfermented product obtained from the edible part of ripe fruit. The soluble solids content (Brix level) of these types of fruit juices represents the level extracted from the fruit."	EU Directives 2012/12/EU (2012), Codex Alimentarius 247-2005
Concentrated fruit juice	Juices that are concentrated and then reconstituted to their original state by mixing with water. The water used has characteristics suitable for human consumption.	
Fruit juice for concentration	Fruit juices intended for concentration must have a minimum Brix level. If the species is not listed in literature, the Brix level is determined in the juices used for concentration (see Table 1).	
Water-extracted fruit juice	Fruit juice extracted with water is obtained through diffusion from the pulp (non-juicy part) of the whole fruit.	
Dehydrated juices	Dehydrated/powdered juices are obtained from concentrated fruit juices by physical treatments (different drying techniques such as spray drying) to remove almost all water content. The product is described as "fruit powder."	
Fruit nectar	Produced by adding water, fruit juice, concentrated fruit juice, fruit juice powder, or concentrated fruit puree. Sugar or honey (>20% w/w) and/or sweeteners may be added. Minimum fruit content depends on the species used (25–50%). Acidity is adjusted with lemon or lime juice or concentrate (3 g/L expressed as anhydrous citric acid). Flavors obtained from fruits through physical processes may be added.	EU Directives 2012/12/EU (2012), Codex Alimentarius 247-2005, Code of Federal Regulations 21CFR101.30
Smoothie	Blended beverages containing fruit pulps and/or purees, sometimes with incorporated yogurt, milk, or chia seeds.	European Fruit Juice Association, 2015
Fruit-based drinks	Non-carbonated drinks not covered by the Fruit Juice Directives because they contain fruit or non-fruit flavors and have less than 25% juice/puree, sugar/sweeteners, acid, flavors, colorings, and preservatives. Often called fruit drinks, fruit cocktails, or "fruit punch."	"*Surprising history of punch*" (History.com, retrieved 27 January 2019)
Clear juice	Transparent, clear juices (particle size <0.001 μm) are water solutions in which total soluble solids (TSS) include sugars, organic acids, salts, free amino acids, water-soluble vitamins, and pigments. Clear juice is obtained through technological clarification of freshly pressed juice.	Dietrich *et al.* (2000); Beveridge (2002)

Opalescent juice	Translucent juices in which soluble substances from clear juices are added. The dispersed phase contains pectins, hemicelluloses, proteins, protein-polyphenol complexes, and starch.	
Classification criteria according to particle size in juice		
Cloudy juice	Unclarified juices not subjected to clarification treatments. Cloudy apple juice (95%) contains all particles <2.5 µm, including proteins, polysaccharides, lipids, and polyphenols. Fine particles originate from cell walls or membranes.	Will *et al.* (2008)
Pulp-enriched juices	Contain a distinct amount of cloud particles (sometimes referred to as pulp) >100 µm, which are fragments from fresh fruit. Pulp-enriched juices can be obtained by blending cloudy juice with fruit puree.	
Classification criteria according to preservation method		
Fresh juice	Freshly squeezed juice not subjected to preservation; short shelf life from a few hours to a few days under special conditions.	European Fruit Juice Association,2015;
Chilled juice	Distributed in the cold chain; marketed and perceived as a product requiring refrigeration. Storage temperature: -1 to 3°C depending on soluble solids content.	
Frozen juice	Distributed in the frozen food chain. Freezing preserves "fresh" characteristics better than other methods. Alternative costs apply for freezing facilities.	British Soft Drinks Association (2016); Bates *et al.* (2001)
Pasteurized juice	Commercially marketed as sterile products with long shelf life at ambient temperature. Heat treatments (pasteurization/sterilization) can be applied to packaged or bulk juice, then packaged aseptically.	Bates *et al.* (2001)
Concentrated juice	Can be stored for extended periods and distributed in ambient, chilled, or frozen commercial chains. Clear juices are concentrated to 72°Bx to ensure microbiological stability under ambient conditions.	

Apple as a raw material in the juice industry

The main raw material is the apple. Globally, there are over 10,000 apple varieties (Butkevičiūtė *et al*., 2020). The world's largest producer of apple juice is Poland. In 2023, Poland recorded a production of 3.89 million tons of apples, and for the 2023/2024 season, the estimated amount of apple juice concentrate obtained from local raw materials was approximately 265,000 tons (Nadulski *et al*., 2025).

The study of the production and commercialization of natural apple juices considered various methods of juice extraction and preservation. Apple juice ranks second among the most purchased and consumed juices, after orange juice. Due to the high cost of storing apples in refrigerated warehouses, producers often send off part of their harvest for processing according to Agromedia (2024). In Romania, apple orchards find favorable conditions for development. The apple tree grows in the form of a tree with a single trunk and a uniform crown.

According to taxonomy, apple belongs to: kingdom *Plantae*, phylum *Angiosperma*e class *Dicotyledoneae*, order *Rosales*, family *Rosaceae*, genus *Malus*, and species *Malus domestica.*

According to organography, the apple is a "false fruit" (pseudocarp). The morphological components of this fruit are: the epicarp (apple peel), the mesocarp (the edible part rich in juice, the pulp), the endocarp containing the seeds, the seminal receptacle and the seeds that are not used in the consumption and technological process (Malladi, 2019).

The nutritional and biological profile of apple

Apples have a high energetic value, sometimes exceeding 85 calories per 100 g. In their fresh state, they contain significant amounts of sugars (7–17%), especially simple sugars, which are easily assimilated. Apples contain organic acids, particularly malic acid (0.16–1.30%), pectic substances (0.5–0.6%), vitamins such as vitamin C (20–40 mg%), vitamin A (0.17–0.45 mg%), vitamins B_1, B_2, biotin, B_6, pantothenic acid, and minerals such as K, Mg, Ca, and Fe, according to Banu (2002).

Impact of season on apple quality and economic implications

The apple tree is a fruit species that adapts very well to temperate climates, having superior resistance to winters. Furthermore, it can be cultivated on various types of soil. Apple orchards located near cities or households contribute positively to the microclimate, favorably influencing temperature, humidity, and air quality. From an economic perspective, apple orchards play an important role, contributing to income growth both nationally and for farmers who follow modern cultivation requirements such as planting distances, irrigation, and crop protection with anti-hail nets. An intensive apple orchard can generate a yield equivalent to that obtained from approximately 5 hectares of cereal crops (Chirla *et al*., 2008).

Certain apple varieties become suitable for consumption during winter (*e.g*., *Idared)*. Unlike other fruits, apples have the advantage of withstanding transportation better and having a longer shelf life than stone fruits. They can be processed into jam, marmalade, preserves, cider, compote, juice. They also serve as a base for other types of marmalade due to their high pectin content.

Apple selection is carried out based on sensory characteristics, since only fruits that provide a pleasant consumption experience are cultivated and kept for human consumption. Before deciding which variety to plant, apples are evaluated. Detailed knowledge of apple varieties and their characteristics is essential before establishing an orchard (Maleca *et al*., 2013). For direct consumption or juice processing, only apples that have reached full maturity are used. Fruits harvested before maturity are unsuitable for consumption or juice production and are instead directed toward producing acidifying agents or used as natural fertilizer by leaving them on the soil according to Crucirescu (2019).

Apples bring numerous health benefits, including: helping regulate intestinal transit due to their high soluble fiber content; contributing to colon cancer prevention; supporting detoxification of the body by eliminating harmful substances; helping reduce cholesterol and regulate insulin levels due to pectin; providing antioxidants, with epicatechin potentially helping reduce blood pressure; supporting weight loss because they are rich in fiber and low in calories, inducing satiety; contributing to cardiovascular health due to their potassium content; offering antioxidant substances that protect the lungs, helping prevent and alleviate asthma symptoms; supporting bone density and strengthening the skeletal system through antioxidant and anti-inflammatory compounds (Minich, 2019).

To best preserve their nutritional properties, apples are processed into juice immediately after harvest or shortly thereafter, since juice yield and compositional quality decrease with storage duration by processing fruits into juices or nectars, some valuable compounds can be retained, using methods such as pressing, centrifugation, or diffusion. The shelf life of the juice can be extended through pasteurization, chemical preservation, concentration, freezing. For apple juice production, varieties with high juice content are recommended, whether sweet, slightly sour, or aromatic. They should be selected to be processed into juice as it is presented in Figure 1.

Apple varieties from the Dâmbovița Valley

The orchards in the Dîmbovița Valley host a variety of modern apple cultivars, adapted both to consumer preferences and to the local climate and soil conditions. Among the most widespread are those presented in Table 2 and figure 2. When selecting apples for juice production, the focus is on sugar content, acidity, and fruit aroma in order to obtain a juice with high quality taste given both by the apple variety and by the way the fruit is maintained and harvested (Marica *et al*., 2022; Marica *et al*., 2024). Agricultural practices such as fertilization, plant protection treatments, irrigation, tree pruning, the use of anti-hail nets, and fruit thinning significantly contribute to improving fruit quality and, implicitly, to obtaining a superior-quality juice. Studies show that in orchards where foliar fertilization is applied, fruit weight increases significantly compared to orchards without such treatments (Balan and Vămășescu, 2015). Foliar fertilization also plays an essential role in the healthy, vigorous development of trees.

Protecting crops against diseases and pests is essential for maintaining fruit quality. This is achieved by applying treatment schemes based on recommendations issued by research and phytosanitary monitoring centers. Final fruit quality is also influenced by pruning and thinning practices. By selecting the fruit buds during formative or maintenance pruning, as well as by thinning flowers (chemically, to prevent pollination) and fruits (manually), proper development of the remaining fruits is ensured.

Correct planting, respecting optimal distances between trees, is essential for their balanced development. Annual pruning also contributes to managing growth and maintaining a balance between vegetation and fruiting (Cimpoieș, 2014).

Hail, frequent in certain regions, can partially or totally damage fruits. Apples struck by hail become vulnerable to microbial contamination, which significantly reduces quality. To prevent these negative effects, as well as sunburn during summer, the use of anti-hail nets is recommended.

Apples intended for juice processing are harvested at optimal consumption maturity and must be healthy, without bruises or signs of deterioration. After harvest, they must be stored under hygienic conditions to prevent microbiological contamination. Cleaning storage spaces and equipment, as well as removing plant residues or foreign bodies, are essential steps for maintaining quality (Babuc et al., 2009). Storage can be done in either normal or controlled atmosphere, characterized by low oxygen and increased carbon dioxide levels (Niculiță *et al*., 1986). Generally, apples are not grown specifically for juice processing, except in some Central European regions where dedicated orchards exist (Lea, 1995). In most cases, fruits are divided into two categories: for fresh consumption and for industrial processing.

Table 2. Apple varieties that grow in the Dîmbovița Valley.

Apple variety	**Description**
Starkrimson	Winter variety derived from Starking, also known as "Rabbit's snout" (Figure 2.a). A small-sized tree that bears fruit on short branches. The fruits are large, elongated, conical, and intensely shiny red. Harvesting begins in early October. The flesh is crunchy, light green, with a slightly aromatic taste; after storage, the texture becomes fine and dense. It can be stored for up to 7 months, after which the pulp becomes mealy. Composition: water 78–89%, sugars 8–17%, organic acids 0.15–1.20%, tannins, pectic substances, proteins, mineral salts, vitamins C, A, and B; caloric intake 46–84 kcal/100 g. It prefers fertile soils and has a low need for irrigation. Frequently used in super-intensive orchards and for juice production
Idared	Intense red color, whitish-green flesh, highly sought after for its long shelf life.
Ionatan	Romanian variety appreciated for its intense aroma and balanced sweet-sour taste, with a crunchy texture and juiciness. Known as "*Ionatan de Voinești*" (Figure 2.b). Popular in Romania, Poland, and Hungary. Sensitive to diseases; in some orchards, it has been replaced by Red Topaz. Used both for fresh consumption and juice production.
Golden (Golden Delicious)	Fruits with a rounded-conical shape, weighing 120–220 g. At physiological maturity, they are intensely green, ripening to a golden-yellow color (Figure 2.e), sometimes with a reddish hue. The flesh is firm, greenish, sweet, fragrant, and juicy. The sweet aroma becomes more pronounced during storage; the flesh darkens in color. Requires controlled atmosphere storage; if kept in dry air, it dehydrates and loses freshness. The fruits are sensitive to apple scab (*Venturia inaequalis*) and powdery mildew (*Podosphaeraleucotricha)*. The fruits contain dietary fiber (2.4–3%), essential minerals (zinc, copper, manganese, potassium), and a high carbohydrate content (13.5–23%) (Marius *et al.*, 2016).
	Apple variety with good resistance to apple scab, widely cultivated in Romania. It has a late blooming period, making it less affected by late

Florina	spring frosts. Medium vigor, requires fewer phytosanitary treatments, and has high and early yield. Can be used as a pollinator for Golden varieties. Medium to large fruits (130–220 g), light red color sprinkled with whitish dots (Figure 2.d). The flesh is crunchy, juicy, aromatic, with a balanced taste – neither too sweet nor too tart. Harvested at optimal time; if overripe, the texture becomes mealy. Good storage capacity until March–April (Minich, 2019). Composition: water 65–75%, sugars 9–15%, organic acids, tannins, pectic substances, proteins, mineral salts, vitamins A, C, B-complex; energy value 46–84 kcal/100 g. When stored at +2°C and humidity >85%, it loses ~20% of its vitamin C in 4–6 months (Marius *et al.*, 2016).
Gala	Small to medium fruit, reddish-yellow skin, sweet flesh. Popular for fresh consumption.
Granny Smith	Intense green, strongly tart. Often used in desserts.
Red Topaz	Modern variety, resistant to drought, diseases, storage, and long-distance transport. Tasty fruits with a sweet-sour combination, juicy and crisp flesh. In years with cold climate and abundant rainfall, the taste becomes more acidic. Slightly flattened fruit, yellow peel with intense red stripes (Figure 2.c). Composition: dry matter 13.5%, sugars 10.5%, vitamin C 11.5 mg/100 g, active substances P 120 mg/100 g, titratable acids 0.6%. Used for fresh consumption and juices.

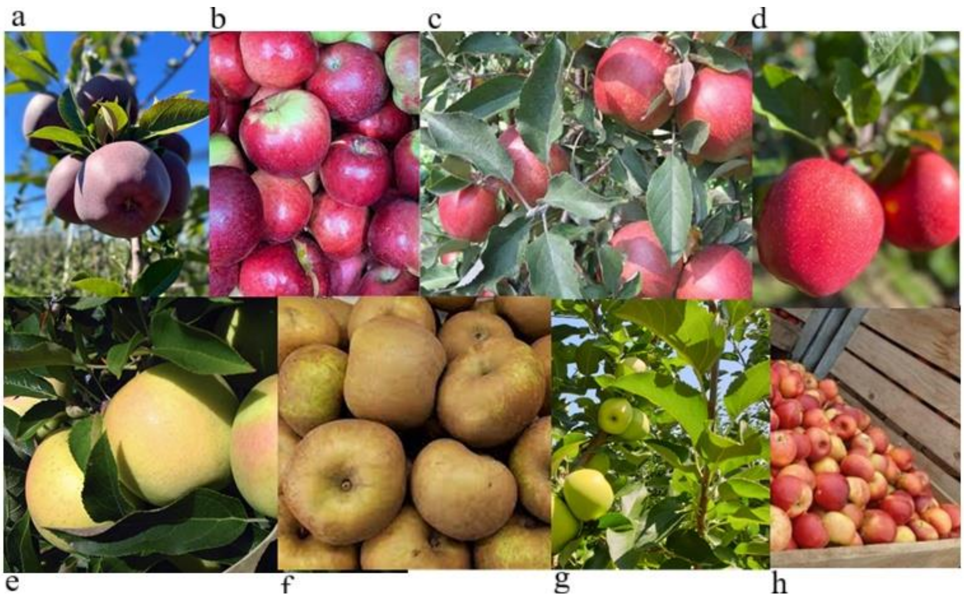

Figure 2. Apple varieties from the Dîmbovița Valley orchard, Romania: a-*Starkrimson*, b. *Ionatan*, c-*Red Topaz*; d- *Florina*; e- *Golden*, f -*Renet*, g- *Sirius*, h-*Rozela*.

To obtain high-quality juice, only healthy apples free from mold, rot, or mechanical damage are used, as their presence can contaminate the product, alter its taste, and reduce its characteristic aroma.

Classical and emerging technologies in juices production

Modern technologies (PEF–pulsed electric fields, HPP–high pressure processing, enzymatic treatments, tangential filtration) tend to replace classical methods, offering apple juices with improved taste, higher nutritional value, and extended shelf life, without the need for aggressive thermal treatments. Additionally, combining suitable varieties (juice blending) and using appropriate packaging contribute to a final product that meets current consumer demands: health, taste, freshness, and sustainability.

Blending

It is recommended to use suitable apple varieties together to obtain higher juice yield and a distinctive aroma. To achieve a flavor appreciated by consumers, several apple varieties are efficiently combined (Marica *et al*., 2022). Juice blending from several apple varieties (*Red Topaz, Starkrimson, Sirius, Rozela, Florina, Golden)* was tested, resulting in a juice with a flavor highly appreciated by consumers, achieving the highest score in sensory analysis. By combining varieties with different characteristics, a final product of superior quality was obtained (Balan & Vămășeanu, 2015).

***Classical mechanical grinding and pressing (Hydraulic or Pneumatic*)**

Extraction time may be reduced to allow rapid transfer of the material to the next technological stage, preventing microbial growth. Beforehand, fruits are sorted and washed, and to prevent oxidation of the resulting pieces, grinding is performed in a saturated steam environment (Gasman, 2016). The efficiency of this process depends on the texture and maturity level of the fruits, which is why a lower grinding intensity is recommended as fruits become riper. After grinding the apples, pressing or juice separation by centrifugation follows. To prevent oxidation, the obtained juice should be quickly transported through closed pipes (Lucaci, 2003).

Enzyme-assisted technology

If the steps are followed correctly, enzymes help break down pectin, reducing turbidity and viscosity, increasing yield (*i.e*., more juice extracted from the same amount of fruit), improving filterability resulting in clearer, easier-to-clarify juice and preserving sensory quality, meaning the natural color, aroma, and taste are maintained (Munoz-Pina *et al*., 2022). Apples are a valuable source of nutrients, including sugars, organic acids, polyphenols, minerals, and dietary fiber. However, in apple juice production, the use of dietary fiber has been limited. In most cases, these fibers remain in the pomace, resulting in the loss of important nutrients. Current enzymatic process optimization focuses mainly on yield, clarity, and sensory properties of the final product. However, the structural variability of the cell wall depending on the apple variety requires specific adjustments to enzymatic hydrolysis conditions. Enzymatic activity is influenced by several factors: enzyme type, reaction time, temperature, enzyme concentration, agitation intensity, pH, and possible interactions between enzymes. Considering these variables, experimental optimization becomes essential for adapting the process to raw material characteristics and maximizing nutritional value. The study aimed to optimize enzymatic hydrolysis conditions for apple juice production from the "*Harlikar" Golden Delicious* variety, focusing on obtaining a product with increased dietary fiber and higher antioxidant capacity. For the first time, a complex enzymatic combination consisting of cellulase, pectinase, xylanase, and α-amylase was reported as effective in intensifying hydrolysis (Xiaoquaiang *et al*., 2024). Extraction yield varies depending on apple variety and is improved using enzymes such as Rohapect PTE-100 and pectinase-based preparations. Sensory analysis revealed consumer preference for the *Rozela* variety, followed by *Starkrimson*, both noted for their pleasant aroma. Future perspectives include combining juices from these varieties, with enzyme addition, to obtain products with improved taste, color, appearance, aroma, and extraction yield. Studies on juices obtained from six apple varieties, both with and without enzyme addition (Pectinase or Rohapect PTE-100), have shown that the variety significantly influences juice quality and that enzymes help improve its properties. For *Starkrimson*, the filtration time was reduced by approximately 50% with enzyme addition. The best results in yield, clarity, and flow rate were obtained using Rohapect PTE-100 (80 ml/1000 kg fruit, 4-hour reaction time, 15–35°C) and Pectinase (10 g/hl, same duration). The *Sirius* variety generated the highest yield, and enzymatic treatment further improved it. Recommended varieties for apple juice production, in descending order, are: *Sirius*, *Rozela*, *Red Topaz, Golden*, *Starkrimson, and Florina.* Although *Florina* variety juice has high viscosity, enzyme addition aids clarification (Marica *et al*., 2025). Experiments were conducted to observe the action of *Penicillium viride* CNMN 04P (a pectinolytic enzyme preparation) to improve apple juice quality. The juice obtained by diffusion exhibited exceptional sensory properties and retained its specific aroma (Clapo *et al*., 2011).

Bottling method

The bottling of the juice significantly influences its shelf life and the preservation of essential nutritional properties. One example is juice pasteurized at 80°C for one minute, which can be packaged in 3-liter Bag-in-Box pouches. The juice is filled hot into the packaging, a process that further contributes to ensuring pasteurization, after which the pouch is hermetically sealed (Marica *et al*., 2022). The packaging consists of three layers of film specially designed for this purpose (Lukhmana *et al*., 2026)

Viscosity-Increasing Agents

Current research focuses on the use of viscosity-enhancing agents in apple juice production. Among these agents, pectin is one of the substances that can be effectively used for this purpose (Liu *et al*., 2025).

High Pressure Processing (HPP)

High-pressure processing represents an effective method for extending the shelf life of apple juice. In the context of increasing demand for healthy and minimally processed foods, modern technologies have been developed to maintain fresh-like product characteristics while ensuring food safety. The processing methods that do not involve high temperatures, such as high-pressure treatment, are attracting increasing research interest. When applied to apple juice, this method has the advantage of preserving the natural color of the product, unlike thermal treatments, while nutritional and sensory properties remain almost unchanged (Walker *et al*., 2000).

Tangential filtration and use of the decanter

Techniques such as tangential filtration and the use of a centrifugal decanter in processing NFC (not-from-concentrate) juices can influence the polyphenol content of the final product. Each method has benefits and limitations, but NFC juices are recognized as the most effective in preserving the authentic aroma and the nutritional value of fruits, including the phenolic compounds. Although it is known that cloudy juices contain more polyphenols than clarified ones, data obtained from the literature, showed that through tangential filtration at low temperatures, such as 40°C, a juice with polyphenol levels comparable to cloudy juices produced by high differential-speed centrifugal decanting can be obtained. Thus, both tangential filtration and centrifugal decanting are viable solutions for producing juices with high polyphenol content. The conclusions of this study provide valuable insights into how different processing methods influence phenolic compound concentrations in apple and pear juices, contributing to the development of optimized technologies for preserving antioxidant value (Yi *et al*., 2017).

High-Intensity Pulsed Electric Field treatment (PEF – Pulsed Electric Fields)

PEF-based technologies have gained an essential role in improving juice quality and safety, contributing to extended shelf life while maintaining superior organoleptic and nutritional characteristics. PEF provides a high extraction yield, largely preserves bioactive compounds and sensory attributes, has low energy consumption, and is easy to adapt and scale industrially. Other methods, such as high-pressure processing (HPP), ultrasound treatment, or microwave-assisted extraction, also have specific benefits, but the overall efficiency of PEF positions it as a reference solution for innovation in the juice industry. Through the controlled application of physical forces, these modern technologies enable more sustainable, efficient extraction processes capable of delivering superior-quality products tailored to current food industry demands (Teixeira *et al*., 2023).

At extraction assisted by PEF apples are sorted, washed, and prepared for processing. By crushing the apples, they are transformed into mash this step is necessary to allow access for the PEF treatment. The apple mash passes through a system where it is exposed to pulsed electric fields. This treatment causes electroporation: cell membranes become perforated, allowing easier release of cell contents (water, sugars, flavors, vitamins). The treated mash is then pressed. Thanks to electroporation, the juice yield is higher than in the conventional method. Filtration removes solid particles and impurities, resulting in a clearer juice. The juice is microbiologically stabilized, whereas PEF technology allows for reduced thermal treatment intensity. This helps better preserve bioactive compounds (vitamin C, polyphenols, flavors). The final product is a juice with superior sensory quality and a richer content of nutrients compared to the conventional method (Torkamani, 2011)

Inhibition of enzymatic browning

A magnetic UVM-7 type material was used for the first time in apple juice treatment, being easily removed afterward due to its optimal magnetite content (approximately 11% of weight). Tests showed that this material also has an effective anti-browning effect, especially in its thiol-functionalized form (Fe_3O_4NPs-UVM-7-SH), which succeeded in reducing enzymatic browning by up to 70%. Additionally, the treatment did not significantly affect beneficial compounds such as vitamin C, flavonoids, or antioxidant capacity total polyphenol content values. It has been suggested that the above-mentioned properties were even higher than those of the oxidized control sample (Muñoz-Pina *et al*., 2022).

Clarified classical Apple Juice

In the classical technologies approaches to obtain clarified apple juice, suitable varieties are chosen, as function of the desired final properties, such as sweet, slightly acidic, and aromatic apples (*Golden, Gala, Red Topaz*, etc.). During reception and sorting, the apples are inspected, and those that are spoiled, unripe, and impurities, dust, soil, and unwanted microflora are removed. The fruits are mechanically crushed to obtain an apple mash (pomace). The resulting mash is subjected to pressing (hydraulic press, belt press, or pneumatic press), producing cloudy juice. The remaining pomace is used as animal feed or for pectin extraction. The cloudy juice is either allowed to settle (decantation) or treated with clarifying agents (gelatin, bentonite, polyvinylpolypyrrolidone). The purpose of decantation is to remove suspended particles (damaged cells, fibers, colloids). In order to remove the suspended particles, the juice is passed through filters (plate filters, membrane filters, or diatomaceous earth filters), resulting in clear apple juice. The juice is then heated (85°C for a short time). The aim of pasteurization is to destroy microorganisms and stabilize the product. The clarified juice is packed in bottles, cartons, or bag-in-box pouches. The final product is clear apple juice, allowing to obtain a product with an extended shelf life (Afraz *et al*., 2024).

Cloudy apple juice NFC – (Not from concentrate)

For cloudy apple juice, the juice is passed through a coarse filter to remove large particles, but it is not fully clarified, retaining its cloudy appearance and natural nutrients. The juice is then packed in special containers (bags, bottles, bag-in-box) (Marica *et al*., 2025).

Freezing for long-term storage or Cryopreservation

The freezing technology in juice industry, for long-term storage involves the steps which are designed to ensure the preservation of quality, safety, and nutritional value of the food over an extended period (Gou *et al*., 2019).

The juice is obtained and then preserved through freezing. Freezing is an efficient method for preserving food products, helping to extend their shelf life. This technique has also been tested for apple juice. The juice is obtained by centrifugation, using healthy apples harvested at optimal maturity and a recipe designed to provide a pleasant taste to the final product. Freezing natural apple juice, without additives, is carried out at very low temperatures, approximately −18°C. Before freezing, the juice is packaged in special doypack-type containers that are resistant to low temperatures (Gou *et al*., 2019)

Membrane clarification technology (ultrafiltration / microfiltration)

Enzymes break down pectins and colloidal substances, resulting in a more fluid juice that is easier to clarify. In order to obtain a clear product, the juice passes through a membrane (micron-sized), allowing that solid particles, cells, colloids to be retained. The juice becomes crystalline and stable (Conidi *et al.*, 2011).

Functional apples-based beverages

Products derived from apples should exhibit organoleptic characteristics similar to those of fresh juice, while simultaneously maintaining the specific nutritional properties of the fruit in its natural state. Various categories of apple juices are available on the market (Table 2), including 100% natural juices, extracted directly from the fruit through mechanical processes such as pressing, without the use of concentrates. These juices may undergo pasteurization through alternative methods and are available in clear or cloudy forms, sometimes enriched with pulp. The fruits used in production may come from both organic and conventional cultivation (Katarzyna and Pawel, 2019). Consumer demands are increasingly focused on foods that provide not only energy and essential nutrients but also health benefits through their bioactive components. In this context, the combination of apple juice with other fruits or ingredients that transform it into a functional food contributing not only to hydration and nutritional intake but also to supporting the immune system and protecting the body against oxidative stress can inspire new nutraceutical product varieties (Mitelut *et al*., 2008). These products are usually stored under refrigeration conditions (European Fruit Juice Association, 2015), yet there is an ongoing concern to extend shelf life without compromising nutritional quality. The clarification process is essential for obtaining clear juice and involves the use of agents such as enzymes, bentonite rich in active substances, or methods of forced sedimentation (Shirvani *et al.*, 2023). Although clear juice is preferred by less-informed consumers, who perceive cloudy variants as impure, studies show that cloudy juice contains a higher concentration of polyphenols. According to the research conducted by Jan Oszmianski from the University of Wroclaw, these compounds have anticancer, antioxidant, anti-inflammatory, anti-allergic, hepatoprotective, and anti-atherosclerotic properties.

Due to their year-round availability and wide distribution, apples represent an important source of polyphenols. Moreover, frequent consumption contributes to reducing the risk of cardiovascular diseases (Wojdylo *et al*., 2020). Consumers show a growing interest in high-quality juices with pleasant taste, affordable price, high nutritional content, extended shelf life, and free from synthetic additives (Braunstein and Crețescu, 2008). The concept of quality involves both the nutritional component represented by carbohydrates, vitamins, and minerals and the technological component, related to cultivation, harvesting, processing, and packaging conditions. Although freshly squeezed juice provides superior nutritional value, the application of preservation methods to extend shelf life may reduce the concentration of bioactive substances. Efforts have been made to enhance the nutritional properties of apple juice through various additives.

Apple juice with added beetroot juice

Iron-deficiency anemia is a common condition among breastfeeding women, affecting both maternal health and the quality of breast milk. Researchers have studied the impact of consuming apple juice combined with beetroot on hemoglobin levels in lactating mothers, highlighting the potential of this mixture as an entrepreneurial initiative. Results showed a significant increase in hemoglobin levels among participants who consumed the juice (Mohame *et al*., 2025). Adding carrot to apple-beetroot juice enhances nutritional properties by increasing β-carotene content (El-Dakak *et al*., 2017). Studies indicate that liquid products based on apple juice apple juice from concentrate, smoothies, and nectars vary between producers depending on the raw material used and weather conditions (Akanda *et al*., 2024).

Enhancement of apple juice with vitamin C, iron, and calcium

These practices aim to increase juices nutritional value. Vitamin C is an important antioxidant that helps protect the body from the harmful effects of free radicals and toxins and plays a crucial role in strengthening the immune system (San Mauro-Martín and Garicano-Vilar,2015). It is also involved in preventing scurvy, cardiovascular diseases, cataracts (Bastias *et al*., 2016). Iron is essential in daily nutrition, contributing to the prevention of anemia. Calcium plays an important role in maintaining bone health, preventing osteoporosis, regulating muscle contractions, and ensuring normal blood clotting. Adequate calcium intake during youth can help maintain long-term vitality (Deleu, 2013).

Apple juice with added fruits

Golden Apple and Monkey kola fruits can be used. Juices were produced from these fruits and mixed in different proportions. Mixed juices with higher Golden Apple content received the highest scores across all sensory parameters, thus increasing consumer acceptability (Okakpu *et al*., 2025).

Apple juice with tea polyphenols

To extend freshness, antioxidant properties, and reduce microbial activity, tea polyphenols are added to apple juice. Nutritional quality and sensory changes were observed in juices with and without added tea polyphenols. Additionally, treated juice had good antioxidant and sensory properties compared to the control group. These results indicate that TP (tea polyphenols) application could increase antioxidant capacity, improve taste, and extend shelf life (Zhong *et al*., 2024).

Smoothies

The smoothies are defined in Table 1. The fruit juice industry generates substantial by-products, such as apple and pear pulp, which are often underutilized despite their nutritional potential. The residual pulp can incorporate microalgae to create nutrient-enriched foods. Apple and pear pulps are used to develop functional smoothies with enhanced antioxidant activity. Microalgae are incorporated as a sustainable protein source. Initially, pulps were treated with PEF (1500–2500V) to reduce colloidal particle size. Three smoothie prototypes were obtained: antioxidant smoothie (pear pulp), protein smoothie with spirulina and apple pulp and protein smoothie with *Chlorella* and apple pulp. The antioxidant smoothie had the highest total protein content (0.67 ± 0.03 g/100 g) (Viegas *et al*., 2025).

Apple juice with propolis

Propolis is a resinous substance produced by bees from plant resins, wax, and enzymes. It is used to protect the hive and has a rich, complex composition (Table3). The final propolis concentration in juices was 0.2 mg/mL (Luis-Villaroya *et al*., 2015).

Table 3. Bioelements of hive products.

Bioelements of propolis and therapeutic effects (Wojdylo *et al*., 2020)	
Chemical composition	Nutritional and functional benefits
Flavonoids	Strong antioxidants (galangin, quercetin)
Phenolic acids	Anti-inflammatory and antimicrobial effect
Vitamins	B_1, B_2, B_6, C, E – in small amounts
Minerals	Zinc, magnesium, iron, calcium – in small amounts
Volatile oils	Antibacterial and antifungal effect
Essential amino acids	Stimulate cellular regeneration
Other active components	Artepillin C (in green propolis), phenylethyl caffeate
Bioelements of pollen and therapeutic effects (Yang *et al*., 2017)	
Chemical composition	Content (varies depending on floral source)
Proteins	20–35% (including all essential amino acids)
Carbohydrates	30–55% (fructose, glucose, polysaccharides)
Lipids	1–10% (including essential fatty acids)
Vitamins	B-complex (B_1, B_2, B_3, B_5, B_6, B_7, B_9), C, D, E, K
Minerals	Iron, calcium, zinc, selenium, potassium, magnesium, phosphorus
Antioxidants	Flavonoids, carotenoids, polyphenols
Enzyme and coenzymes	Important for digestion and metabolism
Fibers	Improve digestion
Bioelements of royal jelly and therapeutic effects (Singleton *et al*., 1999)	
Proteins	~12–15%, all essential amino acids
Carbohydrates	~10–15% – glucose and fructose
Special lipids	~4–6% – unique fatty acids (e.g., 10-HDA, with antiviral effect)
Vitamins	B-complex (high amounts: B_1, B_2, B_3, B_5, B_6, B_9), A, C, D, E
Minerals	Calcium, magnesium, potassium, zinc, iron, copper
Acetylcholine	Important neurotransmitter – supports cognitive functions
Growth factors	Stimulate cellular regeneration
Enzyme and natural hormones	Anti-inflammatory and immunostimulatory effects

The addition of propolis improved the bioactive properties of an apple juice-based dietary supplement. The antioxidant and antibacterial properties of the supplement were enhanced by incorporating propolis into apple juice. A heat treatment was also applied, which destroyed *Escherichia coli* O157:H7. The additive contained 0.2 mg/μL of propolis extracted with propylene glycol (propolis). Regarding antimicrobial activity, propolis (0.2 mg/mL) was highly effective at acidic pH against *Listeria monocytogenes* (EGD-e), but it inactivated or caused sublethal injury to *E. coli* O157:H7 Sakai. However, incorporating propolis (0.2 mg/mL) in an acidic environment reduced the time required to inactivate *E. coli* O157:H7 Sakai at 51°C by over 40-fold. Furthermore, when combined with heat in apple juice, propolis (0.1 mg/mL) reduced both the thermal treatment time and the temperature required for *E. coli* inactivation by 75% respectively. The corresponding concentration of propolis did not induce significant changes on the organoleptic properties of the juice, indicating the possibility of obtaining a sensorially appealing, lightly pasteurized apple juice with functional properties provided by propolis (Luis-Villaroya *et al*., 2015).

Addition of apicultural products simultaneously

Apple juice enriched with honey, royal jelly, pollen, and propolis becomes an exceptional nutraceutical beverage, ideal for supporting immunity, energy, detoxification, and regeneration. It represents a natural alternative to dietary supplements, suitable for adults and children (with caution and age adaptation) (Marica *et al*., 2025).

Apple juice with added honey

Marica *et al*. (2025) obtained a functional apple-based beverage with honey addition, by using 100% apple juice produced by cold extraction, pasteurized at 80 °C for 1 minute, and then rapidly cooled to 35 °C before adding approximately 5% honey. The juice was immediately bottled using aseptic Bag-in-Box packaging. This ensures that the nutrients from honey are preserved in the juice. The juice is enriched with natural sugars (glucose and fructose), contains enzymes such as glucose oxidase with antibacterial effects, antioxidants such as flavonoids and phenolic acids, vitamins (B_1, B_2, B_3, B_5, B_6, C), and minerals including calcium, iron, magnesium, zinc, potassium, and phosphorus (Work, 2018). The nutritional value, antioxidant effect, and functional properties (potential antibacterial and anti-inflammatory) of the juice are thus enhanced (Collazo *et al*., 2021; Botezan *et al*., 2023).

Apple juice with added pollen

Pollen is one of the most complete natural foods, with an extremely rich composition presented in Table 3b. Apple juice enriched with pollen improves its nutritional value, antioxidant capacity, and the digestive and nutrient absorption potential due to natural enzymes. Its fiber content helps regulating the intestinal transit. Phytonutrients support immunity and have anti-inflammatory effects (Calmuțchi *et al*., 2021).

Apple juice with added royal jelly

Royal jelly is a natural superfood secreted by worker bees to feed the queen bee. Adding royal jelly to apple juice significantly enriches the beverage nutritionally and functionally, transforming it into a natural elixir with multiple health benefits. It has a unique composition, presented in Table 3c. Apple juice with added royal jelly enhances its nutritional and therapeutic value, providing amino acids for regeneration, B-group vitamins for energy metabolism and nervous system function, acetylcholine for brain activity, antioxidants for protection against oxidative stress, fatty acids with immunomodulatory effects, and essential minerals for muscle and cardiovascular function (Peykova-Shapkova *et al.*, 2025).

Classical and modern methods for investigating juice quality

The quality of juice is determined using classical physicochemical methods and standardized modern instrumental techniques in order to obtain a comprehensive overview of chemical composition, sensory properties, and nutritional value. Quality indicators such as pH, titratable acidity, volatile acidity, soluble dry matter, relative density, turbidity, kinematic viscosity, sensory characteristics, and the Brix/total acidity ratio can be evaluated alongside the determination of various bioactive compounds important for quality and stability, such as sugars, polyphenols, anthocyanins and vitamin C.

As analytical techniques, these analyses can be complemented by spectrophotometry and HPLC (High-Performance Liquid Chromatography), which provide precise data on phenolic and organic acid composition. Capillary electrophoresis and thin-layer chromatographic methods have enabled the identification and quantification of sugars and other specific components. In parallel, sensory and instrumental colorimetric evaluations have provided information on key physical properties that significantly influence consumer acceptance of the product.

Antioxidant activity, enzymatic activity, and fiber content can highlight the functional potential of the juice, while the calculation of nutritional value integrates these data into a holistic perspective on nutrient intake. Thus, the combined approach allows differentiation of juice assortments according to raw material, processing technology, and the additives required for developing the functional properties of the final product.

Market perspectives

Increasing consumer interest for natural functional beverages

In recent years, there has been a pronounced trend among consumers toward products that combine natural characteristics with functional health benefits. Functional beverages, especially those derived from local fruits, are perceived as healthier alternatives to carbonated drinks or beverages containing artificial additives.

Apple juice, due to its high content of polyphenols, flavonoids, vitamin C, and soluble fiber, fits perfectly into this category (Doyen and Couillard, 2022). Modern consumers increasingly seek minimally processed products, free from synthetic preservatives and with clear traceability of origin. Thus, apples cultivated in the Dîmbovița region and valorized through innovative processing technologies can support the development of a regional functional product that meets current market demands.

Waste reduction through by-product valorization

Apple juice production generates significant quantities of by-products (pomace, peel, and seeds), which are often treated as waste. However, these components are rich in bioactive compounds with high functional and industrial value. Modern technologies such as ultrasound-assisted extraction, green solvent extraction, and high hydrostatic pressure enable the recovery of these secondary resources for obtaining pectin, dietary fiber, and bioactive compounds. The reduction of chemical fertilizers and additives contributes to obtaining juice perceived as safer and nutritionally more valuable (Rupasinghe and Yu, 2012). Additionally, the industry is moving toward biodegradable (bioplastic) and recyclable packaging solutions, such as bottles made from plant-based biopolymers, compostable materials, or cellulose fiber packaging (Zhao, *et al*, 2023). These approaches not only reduce waste but also strengthen the ecological image of the product.

Conclusions

The study highlights the importance of using quality raw materials and applying modern technologies in the process of obtaining apple juice, with a direct impact on the nutritional value and sensory properties of the finished product. Enzymes, especially pectinases, play an essential role in this process, and significantly contribute to the efficiency of juice extraction, the reduction of must viscosity and the improvement of product clarification. Through their action on pectic compounds in the cell walls of fruits, enzymes facilitate the release of bioactive compounds and natural sugars.

Thus increasing the yield and quality of the obtained juice. In the case of cloudy juices, enzymes help maintain colloidal stability and obtain a pleasant texture, without compromising the natural content of fibers and phytonutrients. The analysis of cloudy apple juices demonstrated their potential to provide a superior intake of bioactive compounds and fibers, constituting a more valuable alternative from a nutritional point of view compared to clarified juices. The use of modern testing technologies allows for precise monitoring of the manufacturing process, recipe optimization and product stability. Overall, the analysis methods contribute to creating a safe, nutritious and competitive product on the market, representing an essential link in the apple juice production and quality control chain. Overall, the research highlights the major role of the apple variety selection, the enzymes used, the appropriate technological processes and the qualitative analyses in obtaining products with real benefits for the consumers and with competitive potential on the functional beverage market.

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