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Processing apple pomace powder to reduce environmental pollution

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Apple pomace is a polluting waste and is unsuitable for feeding livestock. Various alternative solutions for the use of apple pomace when implemented in practical conditions can contribute to the development of a technological chain of waste-free apple processing. The by-product – apple pomace – is rich in valuable fiber in the form of pectin substances. Therefore, their processing is of great importance for environmental protection. The paper presents a comparative content of pectin in various plant raw materials and the chemical composition of pectin and the elemental composition of pectin powder in apple pomace, which allows these wastes to be used as an ingredient in the production of food products, in particular in the meat and soft drink industries to reduce the amount of sugar and increase the biological value of the product. The article shows the possibility of using pectin for the production of edible film to protect food products, antimicrobial biofilms, nanoparticles, etc., which extends the shelf life of food. Advances in the use of different extraction sources and knowledge of structural modification have significantly expanded the properties, yield and applications of pectic substances found in apple pomace. Modified pectin has shown better functional properties than native pectin. It has been established that pectin can be used in biomedicine as a targeted application in the delivery of bioactive drugs and to stop the spread of cancer cells in the lungs. During the review of literature sources, the possibility of using apple pomace in the production of bioethanol was considered, which will positively affect environmental processes in the future. The obtained data contain practical value regarding the possibility of waste-free processing of apple pomace in various sectors of the national economy, which is currently a relevant issue.

Keywords: waste; pectin; biomedicine; biofuel; food coating.

Introduction

Apple pomace accounts for 20–25% of each apple processed for juice. The amount of apple pomace is growing every year, and its consumption by livestock in such quantities is impossible. Therefore, throwing pomace into the environment makes it ecologically unclean, which must be combated (Nikolaenko, 2021). Residual amounts of pomace are increasing every year, as apple processing is increasing. Therefore, the production chain from raw material processing to obtaining the finished apple juice product must pay attention to residues in the form of apple pomace.

Apple pomace is the pulp, skins, seeds and stems that can be processed to produce high-value products and is a bioresource of functional and nutritional components with potential for use in various food formulations (Kauser et al., 2024).

After drying and grinding, apple pomace can be added to bread and meat products, increasing the amount of dietary fiber and providing antioxidant properties to the finished food products (Palamarchuk et al., 2024b). Phenolic extracts obtained from pomace or fiber extracts are also food ingredients. Apple pomace can be a raw material for the production of food packaging for products and food films, as well as for the production activated carbon. Ursolic acid and cutin obtained from apple peel can be used in the pharmaceutical industry and for developing materials and films, respectively. Apple seeds are also a source of oils that are used as raw materials for the perfume and cosmetic industry (Manrich, 2024). For example, in India in particular, the total amount of apple pomace produced is about one million tons per year, and only about 10,000 tons of apple pomace is used for processing (Shalini & Gupta, 2010).

Apple pomace can be used to obtain food pectin because it is rich in pectic substances and fiber and other carbohydrates, rather than being thrown away and causing environmental pollution (Prystash et al., 2024; Zhang et al., 2024a; Zheplinska et al., 2025). According to research by Zheng & Shetty (2000), apple pomace contains a number of other ingredients, including vitamins, minerals, and proteins. The use of apple pomace in the production of bioproducts is a future challenge for environmental protection (Rebolledo-Leiva et al., 2024).

Pectin in the food industry

Pectin is sensitive to physicochemical and enzymatic changes because the numerous functional groups present in its structure can induce different functionalities, and certain modifications can lead to pectin applications in food, agriculture, pharmaceuticals and biomedicine. The nutritional applications of pectin hydrogels can be divided into four categories: food ingredients/additives, food packaging, bioactive delivery and health management (Ishwarya et al., 2022). Pectin is successfully used in the food industry as a thickener and gelling agent, and in beverage production as a colloidal stabilizer.

Table 1 presents the pectin content in various plant raw materials or production waste. Among root crops, sugar beet stands out, which can contain up to 30% pectin. However, there, pectin is in the form of protopectin, i.e. insoluble pectin, and accordingly its gelling properties are low. The picture is approximately the same regarding the pectin content in table red beet. But from carrot pomace, where the amount of pectin is half as much but is soluble, a sufficiently large amount of pectin can be obtained. As for the fruit group, according to scientists, pineapples can contain 54% pectin. Unlike pineapples, the amount of pectin in peaches reaches only 10%. Apple pomace, lemon and orange peels also contain a sufficiently large amount of pectin, which can be obtained by extracting it from waste. And given the fact that a large number of apples are processed primarily into juice, a considerable amount of waste is produced from them, namely apple pomace, which can and should be processed so as not to harm the environment.

Due to its unique functionality, pectin forms three-dimensional (3D) hydrophilic polymer networks, giving these hydrogels softness, flexibility and biocompatibility. Their exceptional properties surpass those of other biopolymer gels, demonstrating rapid gelation and potential use in the food industry (Nath et al., 2022; Said et al., 2023).

Table 1
Pectin content in various plant raw materials

Ref. No.	Raw	Pectin content, %	Source link
1	Table beet	8.0–28.0	Yancheva et al. (2016); Zheplinska et al. (2023)
2	Sugar beet	18.0–30.0	Yancheva and al. (2016); Vasyliv et al. (2022)
3	Carrot	15.0–16.0	Jafari et al. (20 17)
4	Peaches	up to 10.0	Valdes et al. (2015)
5	Pineapple	54.0	Begum et al. (2017)
6	Pomace	10.0–17.0	Fajardo et al. (2016)
7	Lemon peel	20.0–30.0	Panchami & Gunasekaran (2017); Fajardo et al. (2016)
8	Orange peel	30.0–50.0	Begum et al. (2017)

Note: developed by the authors based on data from researchers.

Research by Panchami & Gunasekaran (2017) showed that citrus peel contains a high pectin content of approximately 24.5%. They examined fruit wastes such as citrus peel, mango peel, apple pomace and banana peel, which were subjected to an extraction process to obtain the corresponding pectin. Since citrus peel was found to contain a significant amount of pectin, the authors recommend further studies to isolate the enzyme pectinolytic from citrus wastes.

Extraction of pectins from sugar beet pulp was carried out by Yapo et al. (2007). They used an aqueous-acidic medium, changing the pH value, the duration of the process and the temperature level. The yield of extracted pectins ranged from 4.1 to 16.2%. Moreover, galacturonic acid accounted for 35.2–76.3%, sugars – 6.8–32.9%, methoxy groups were in the amount of 2.0–4.2%, acetyl groups were in the range of 0.8–3.8%, and ferulic acid was from 0.1% to 0.7%. Traces of protein were present in all extract samples and their amount varied within 0.9–6.8% depending on the extraction conditions. Using the exclusion chromatography method, two broad peaks were established, which allow us to state that most of the extracted pectins were surface-active, and they are able to produce and effectively stabilize oil-in-water emulsions. This means that the yield, physicochemical parameters and surface properties of acid-extracted pectins from sugar beet pulp are influenced by the extraction conditions (Levin et al., 2002). Pectin is a polysaccharide with compatible intrinsic biological activity that can have different structures depending on the source and extraction method. Among the various industrial by-products, this polysaccharide appears as a green option for the valorization of agro-industrial waste by producing a product of high commercial value (Freitas et al., 2021). These scientists found that the highest average pectin yield of approximately 14% was obtained when the particle size for extraction was in the range of 106 to 250 μm.

Consuming a large amount of saturated fat leads to huge health problems for people. Therefore, the use of fat encapsulation with carbohydrates, such as pectins, is an alternative to reducing the intake of fat from meat products by preventing its digestion and absorption (Santiagín-Padilla et al., 2019).

Currently, the main sources of commercial pectin are citrus peel, apple pomace, and sugar beet pulp (Dranca & Oroian, 2018).

In most cases, apple pomace is used at 5–30%. For their more complete use, a technology has been developed for obtaining pectin substances from fresh apple pomace by alkaline hydrolysis, which is based on the property of protopectin to become soluble in an alkaline environment at a pH value in the range of 8.0–12.0. The use of such a pectin extract makes it possible to significantly reduce energy costs for production and obtain standardized products – pectin with a dry matter content of 9.0%. According to Moskalyuk (2011), the chemical composition of such pectin includes reducing substances in the amount of 5.5%, pectin substances – 0.98%, water-soluble substances – 7.0%, alcohol-soluble substances – 3.9%, mineral substances – 0.6%, hemicelluloses – 5.5%. The titrated acidity of pectin is 0.6%, the pH value is 5.0 units, and the degree of esterification is 54.5%.

Danilenko et al. (2018) determined the elemental composition of pectin powder from apple pomace using the spectrometry method. According to scientists, the micro- and macroelement composition of pectin powder from apple pomace contains iron in the amount of 32.87%, potassium – 18.12%, magnesium – 16.11%, phosphorus – 15.71%, sodium – 7.31%, zinc – 4.16%, manganese – 3.31%, copper – 2.40%, iodine – 0.67% and calcium – 0.34%. The large amount of phosphorus, iron, potassium and magnesium in the obtained powder allows us to state that pectin powder from apple waste can act as a functional ingredient for food products to reduce the amount of sugar and increase the biological value of the product. However, several times smaller amounts of copper, zinc, manganese, and sodium do not reduce their role in food products.

Studies by Canteri-Schemin et al. (2005) found that pectin extraction using apple pomace as raw material gave a lower yield of pectin than when using apple flour. This result showed that it is necessary to produce apple flour as an intermediate stage of acid extraction of pectin from pomace. Extraction of pectin from different varieties of apple pomace according to the results of the studies did not show a significant effect on the yield of pectin. Among the studied organic and mineral acids, citric and nitric acids showed the highest yield. Apple pectin had a degree of esterification of about 69%.

Sharma et al. (2014) optimized the method of extracting pectin from apple pomace for commercial use. Fresh pomace allowed them to obtain 13.3% pectin by dry matter content. Blanching pomace at a temperature of 95 °C for 5 minutes with subsequent cooling and drying at a temperature within 50–52 °C turned out to be a necessary pretreatment before the pectin extraction process. When establishing the optimal method of pectin extraction, a 0.05 N HCl solution was used at a temperature of 95 °C for 1 hour with subsequent precipitation in 95% ethyl alcohol. In this case, the pectin yield was 10.5%. According to the researchers' results, pectin was characterized by an anhydrogalacturonic acid content of 59.1%, a degree of esterification of 71.2% and a jelly-like degree of 110 units.

The pectin obtained from apple waste can be used as a component of bio-nano-packaging, which is a nutraceutical concept (Nakash et al., 2017).

Antonenko et al. (2022) developed a dessert "Bird's Milk" with low-esterified pectin, calcium citrate and polydextrose, which provides an expanded range of dishes for adults and children with an increased content of essential nutrients, improved consumer properties of the product, which contributes to the preservation of public health, protection from the negative effects of the environment. The finished product has an increased content of dietary fiber, vitamins and minerals compared to traditional technology. The developed culinary product can be recommended for daily diets of people working in heavy industry, living in environmentally contaminated areas, since the pectin contained in the product acts as a radioprotector.

Use of apple pomace in food products

In recent years, there has been a trend towards people becoming more aware of the connection between food consumption and health. Many studies are aimed at product development for the meat industry using meat product formulations with herbal additives, which leads to improved functional properties of the product (Sharefiabadi & Meltem, 2021; Zheplinska et al., 2022a; Chechitko et al., 2024).

Pectin is a water-soluble fiber found in the cell walls of fruits and vegetables. It helps reduce the risk of cancer and is a radioprotector that accumulates heavy metals, radionuclides and pesticides. Pectin has the ability to gel, which makes it a unique substance. The catalyst for this is Ca^{2+} ions or sugars and acids. In addition, pectin binds water and fat well (Kryzhova et al., 2023). Therefore, it can be used as a gelling agent, film or coating and emulsifier, and also used in low-calorie meat products as a fat and sugar substitute. Sharefiabadi & Serdaroglu (2021) devoted their work to such properties of pectin.

Gullón et al. (2007) investigated experimental samples of apple pomace in the production of cider for chemical composition and enzymatic digestibility. They found that alcohol-soluble compounds such as monosaccharides, oligosaccharides and malic acid accounted for 32% to 45% of the mass of dried pomace, with glucose and fructose accounting for the bulk of this fraction. The alcohol-insoluble fraction accounted for 55–68% of the mass of dry apple pomace and mainly consisted of neutral fiber and pectin. The content of nitrogen, phosphorus and metal ions in pomace – potassium, magnesium, iron and manganese – was favorable for the subsequent manufacture of media for lactic acid fermentation. Apple pomace showed high susceptibility to enzymatic hydrolysis. Therefore, the authors argue that apple pomace is a promising raw material for the production of lactic acid.

Choi et al. (2016) investigated the effect of reducing the level of pork fat from 30% to 20% by partially replacing pork fat with 1–2% apple pomace fiber. The studies were conducted based on the evaluation of physicochemical and textural properties of non-dried chicken sausages with reduced fat content. The results showed that the increased fat level led to a decrease in moisture content, cooking loss, fat separation and yellowing of raw chicken sausages. With increasing fat content, the calorie content, pH value, hardness, cohesion, stickiness and chewiness of the meat product increased. In contrast, raw chicken sausage samples with reduced fat content and increased apple pomace fiber had lower cooking loss, fat separation, pH value and redness. Thus, adding apple pomace fiber to the recipe allowed the fat content to be reduced in emulsion sausages, while improving the quality characteristics of the finished product.

Apple pomace with a total dietary fiber content of 62.67% showed high water and oil retention capacity, antimicrobial activity against *S. aureus*, *P. aeruginosa* and *L. monocytogenes*. Buffalo sausages containing apple pomace powder showed high cooking yield and emulsion stability compared to the control sausage. In addition, dietary fiber content was improved by the inclusion of apple pomace powder (Younis & Ahmad, 2015).

Yadav et al. (2016) conducted research on the development of chicken sausage, which is enriched with dietary fiber from corn waste, apple and tomato pomace. They replaced meat in the recipe with corn bran, dried apple and tomato pomace at 3, 6 and 9%, respectively. The organoleptic assessment of such sausages was high and they were stored for up to 15 days under refrigerated conditions.

Due to the lack of dietary fiber in meat (Melnyk et al., 2024) it is combined with various fruits and vegetables, which are rich in dietary fiber. Ahmad et al. (2020) found an effective interaction between dietary fiber and meat protein, manifested in a negative binding free energy. Mendes-Zamora et al. (2015) found that replacing fat with inulin and apple pectin in the production of sausages led to an increase in the organoleptic perception of sausage products, which can be attributed to healthy and functional products.

American researchers Schmile et al. (2015) found that fiber intake in general leads to weight loss, especially in women. Therefore, the use of apple pomace in the human diet is of great importance for establishing the relationship between dietary variables and body mass index. Thanks to bioactive substances, apple pomace can form emulsions while maintaining oxidative and physical stability (Lu et al., 2020). The inclusion of apple pomace in yogurt products and beverages improved their emulsion stability and textural characteristics (Wang et al., 2020). Kapoor et al. (2023) found that apple pomace is a good source of carotenoids, phenols, and flavonoids for the production of commercial jams.

Edible pectin film for food coating

Edible films, which are made of polysaccharides, proteins, and lipids, extend the shelf life of food products by functioning as barriers to solutes, gas, and vapor (Gennadios & Kurth, 1997; Falguera et al., 2011). In addition, such coatings can serve as carriers for antimicrobial compounds to maintain high concentrations of preservatives on the surface of food products. Although the use of edible films to preserve food quality is not a new concept, research in this direction by scientists has recently intensified. After all, all this affects the consumer demand for high-quality food products; the needs of food industry enterprises in new technologies for storing both raw materials and finished products; environmental issues regarding the disposal of non-renewable packaging materials for food products; opportunities for creating markets for film-forming ingredients for meat, poultry and seafood obtained from recycled agricultural raw materials (Gennadios et al., 1997). Ravishankar et al. (2012) developed antimicrobial edible food films made from apple and carrot pomace and hibiscus calyxes. Such films can be used in the food industry to inactivate *Listeria monocytogenes* on ready-to-eat meat products such as bologna and ham. This research provides a broad-scale application of edible films based on fruit and vegetable waste for food products to improve their microbial safety.

The use of edible films in aquaculture with features of gas, moisture and vapor permeability and adhesion of coatings also takes place, which was studied by researcher Korkmaz (2018). The use of such films eliminates the problem of waste and reduces the risk of carcinogenic effects of finished products. Especially in meat products with edible coatings, fat oxidation is reduced or prevented. Vitamins present in the coating stop the darkening reactions, and the aroma of the finished product does not change, and the pigments remain in the products. All this has made these films very popular recently.

Kang et al. (2007) studied the physicochemical, microbiological and sensory properties of cooked pork cutlets coated with a pectin containing green tea leaf extract powder. The coated finished products contained a higher moisture content than the air- and vacuum-packed controls. The total aerobic bacteria count was significantly lower due to the coating treatment as well as irradiation. No difference in sensory properties was found due to gamma irradiation or coating.

Liu et al. (2007) in their studies used casings formed from pectin containing 2.5% corn oil and 5% olive oil for sausage production. The organoleptic indicators of sausage products with this casing showed exceptional resistance to lipid oxidation during six days of storage and were less than one on the TBARS number scale.

A food film based on pectin and red cabbage was developed by Dudnyk et al. (2018) which is convenient to use primarily for meat and fish, that have the ability to spoil. The edible film in this case has high sensitivity to gaseous amines with a clear colorimetric change, which prevents rapid spoilage of raw materials or finished products.

Modern genetic engineering allows the production of modified pectins with ionotropic gelation and gel coating. Given the safe toxicity profile of pectin, it makes it a promising substance for the food and pharmaceutical industries (Narasimhan & Sethuraman, 2016).

Using apple pomace in the form of pectin in medicine

Pectin is an exceptional natural polymer due to its unique functionalities and excellent properties, such as biocompatibility, biodegradability, low cost, and easy gelation ability, which has attracted significant interest in drug delivery fields (Han et al., 2022). Pectin is a complex, versatile heteropolysaccharide of great importance to the pharmaceutical industry. It is widely used in biomedical and biomaterial applications due to its potential anti-inflammatory and immunomodulatory effects, as well as its biodegradability and biocompatibility. The multifunctionality of pectin is due to the nature of its molecule, which has a diverse chemical structure, physicochemical properties and potential functionalities depending on the sources from which it is extracted and the extraction methods (Roman-Benn et al., 2023).

A review by Fathi et al. (2012); Krupodorova et al. (2024) summarized the research on various pharmacological activities of pectin, namely immunoregulatory, anti-inflammatory, hypoglycemic, antibacterial, antioxidant and antitumor activities. Pectin has become an integral part of the research and development of natural herbs and health products due to its wide availability.

Li et al. (2020) synthesized innovative silver (Au) nanoparticles with immobilized pectin-modified magnetic nanoparticles (Fe_3O_4 / Pectin / Au) for the catalytic reduction of nitroarenes and investigated their anticancer activity against human lung cancer. MTT assay investigated the cytotoxicity of nanoparticles with normal cancer cell line HUVEC and three cancer cell lines LC-2/ad, PC-14 and HLC-1. In each case, the percentage of cell viability decreased with increasing concentration of the nanocomposite. PC-14 cell line showed the strongest cytotoxic results of the synthesized nanocomposite and potential against human lung cancer.

Chang et al. (2022) created a self-healing pectin/cellulose hydrogel loaded with limonin for the treatment of lung cancer. The authors investigated limonin, a herbal medicinal compound that inhibits lung tumor growth and promotes apoptosis by affecting the highly expressed ion channel TMEM16A. The hydrogels exhibited rapid gelation, excellent biocompatibility, and sustained release of limonene properties. The limonin/hydrogel combination demonstrated acceptable anticancer effects and reduced side effects *in vivo*, combining the antitumor properties of limonin and hydrogel.

A review of the health benefits of pectins justifies their inclusion in human diets and biomedical products. For example, Zhang et al. (2021b) presented methods for extraction and modification of pectins, their physicochemical parameters, the health-promoting properties of pectins and their applications in pharmaceuticals. Pectins, as universal biomolecules, can be adapted for pharmaceutical and biomedical applications by a reasonable choice of appropriate extraction processes, which are based on the principles of ecological chemistry. The structural and physicochemical parameters of pectic substances and pectin in particular determine its effect on the digestive process and the bioavailability of nutrients, as well as properties that promote health, including antitumor, immunomodulatory, anti-inflammatory properties. Pectin also regulates the intestinal microflora, strengthens the immune barrier, prevents atherosclerosis, exhibits antidiabetic properties, prevents obesity, has antitussive, analgesic, anticoagulant and wound-healing effects. Achieving beneficial interactions between extraction processes and method modifications during pectin production, as well as between pectin and other components in biomedical products, should be a key area of future research according to the authors of the paper.

Biofuel

Producing bioethanol from waste feedstocks, including apple pomace, and using such ethanol as fuel can reduce fossil fuel consumption and its environmental impact. As energy -saving alternatives to conventional distillation processes, Gavakhian et al. (2019) show newer environmentally friendly distillation methods, such as ohmic hydrodistillation, membrane distillation, and integrated heat methods. In addition, a number of valuable components such as pectin and bioactive compounds such as phenolic compounds have been isolated from bioethanol production wastes using various environmentally friendly valorization methods. These novel distillation and extraction methods can be implemented to develop a more environmentally friendly bioethanol production process in the future.

Considering that approximately 85% of the total energy used by society comes from fossil fuels, these are currently the most important energy sources available (Palamarchuk et al., 2024a). Given that fossil fuel reserves are decreasing and have a negative impact on the environment, it is necessary to look for renewable and viable alternatives, such as biofuels. One of the most famous types of biofuels is biodiesel, which consists of a mixture of alkyl esters of fatty acids. As pointed out by Leung et al. (2006), the physicochemical properties of biodiesel are similar to conventional diesel fuel. Therefore, its use when mixed with petroleum diesel does not require engine adaptation. Biodiesel also has a number of advantages, which are manifested in lower toxicity, emissions of pollutants (carbon monoxide, sulfur dioxide, particulate matter, polycyclic aromatic hydrocarbons and aldehydes), as noted by Marinković et al. (2016). Due to the chemical similarity of biodiesel to natural oils and fats, its degradation in the environment occurs rapidly, reducing the environmental impact (Mardhiah et al., 2017). For these reasons, this biofuel can be considered a viable alternative to petroleum diesel.

Biodiesel is usually produced by the transesterification of triglycerides, such as vegetable oils or animal fats, with methanol or ethanol. A molar ratio of 3:1 with respect to triglycerides is required. However, since the reaction products are in equilibrium with the reactants, an excess of alcohol is used to achieve sufficient conversion (Meheet et al., 2013).

Researchers Szabados & Bereczky (2018) used pectin for experiments as a modifier to obtain active CaO for biodiesel production, due to its high availability, low cost, and the presence of carboxylic acid groups in the D-galacturonic acid chains, which have the ability to effectively complex Ca^{2+} ions (Maciel et al., 2015). Calcium oxide obtained with the addition of pectin demonstrated higher catalytic activity and a significant reduction in the amount of calcium leached into biodiesel, meeting international standards without the need for additional washing steps.

Therefore, the results obtained by scientists suggest the production of various products in the food and processing industries based on apple pomace. Our recommendations are of speial relevance for manufacturers of the food, pharmaceutical and processing industries, who should think about the rational use of apple pomace and the huge opportunities to use this secondary raw material for commercial purposes with waste-free production and environmental protection.

Conclusion

To reduce environmental pollution, it is worth using apple pomace as a raw material for producing various products. This paper shows the benefits of pectin obtained from apple pomace and its application in meat production and the development of beverages using apple pomace. The chemical composition of pectin and its elemental composition are presented, based on which a conclusion can be drawn about the feasibility of its use in the field of nutrition.

Food coatings or films based on pectin protect the product from mechanical damage, chemical and microbiological action. Their use in food products, especially for perishable products, is based on cost, availability, functional characteristics, barrier effect against gases, structural resistance to water and microorganisms, as well as organoleptic properties. All this allows the shelf life of finished products to be extended, especially meat products. The physicochemical properties, biocompatibility and biodegradability of pectins allow the creation of edible films based on pectin.

In biomedicine, the use of pectin as a natural sorbent capable of forming poorly soluble complexes with ions of heavy metals, pesticides, and radionuclides allows the production of drugs with enveloping functions.

New methods of distillation and extraction of pectin from apple pomace can be implemented to develop a more environmentally friendly bioethanol production process in the future.

Therefore, the problem of waste accumulation disappears by processing apple pomace for commercial purposes to obtain new products of food, pharmaceutical or industrial value.

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