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REVIEW

Transforming Apple Pomace into Valuable Resources: Upcycling for Carbon Reduction and Circular Resource Utilization

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Abstract

The global apple processing industry generates millions of tons of apple pomace (AP) annually, leading to significant environmental challenges owing to improper disposal methods, such as landfilling, which releases methane and other contaminants. This mini-review provides a concise overview of the strategies for the upcycling and circular resource utilization of AP. Upcycling strategies for AP can contribute to environmental protection through carbon reduction and resource circulation using existing resources in new methods instead of new materials. Additionally, this review presents the potential of AP as a raw material for food, pharmaceuticals, and cosmetics while examining the technical, economic, and environmental challenges and necessary improvements for its optimal use. Overall, the upcycling of AP offers a valuable opportunity to improve waste management and promote efficient resource utilization.

Key words: Food industry, Landfilling, Resource circulation, Waste management

1. Introduction

The global apple processing industry generates millions of tons of apple pomace (AP) annually, resulting in significant environmental challenges (Dhillon et al., 2013; Abdessemed et al., 2022; Golebiewska et al., 2022). AP, a by-product of apple juice and cider production, represents a large volume of waste and poses significant disposal challenges. Improper disposal methods, such as landfilling, release methane, a potent greenhouse gas that accelerates climate change and contributes to environmental pollution. Additionally, leachates from decomposing AP can contaminate soil and water, leading to further ecological risks (Rana et al., 2021; Siddiqua et al., 2022; Kauser et al., 2024).

According to Statistics Korea, the apple cultivation area in South Korea increased from 34,359 ha in 2021 to 34,603 ha in 2022, with apple production also rising from 515,931 tons to 566,041 tons, an increase of 50,110 tons. In 2022, the distribution of cultivation area and production by province was as follows: Gyeongbuk (330,532 tons, 20,685 ha), Gyeongnam (77,610 tons, 3,820 ha), Chungbuk (58,640 tons, 3,703 ha), Jeonbuk (42,618 tons, 2,317 ha), Gangwon (24,852 tons, 1,630 ha), and other regions (31,789 tons, 2,448 ha) (Statistics Korea, 2022).

According to Ministry of Agriculture, Food and Rural Affairs, 46,406 tons of apples were

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processed in South Korea in 2022, making apples the second most processed fruit after Satsuma mandarins (63,909 tons). The processed apple products mainly included juice (40,512 tons), beverages (2,202 tons), apple extract (1,277 tons), cider (876 tons), and jam (527 tons) (Ministry of Agriculture, Food and Rural Affairs, 2022). Following apple processing, substantial amounts of AP, a by-product, are generated. The majority of this byproduct is treated as industrial waste. The high acidity and seed germination-inhibiting properties of AP contribute to significant environmental challenges (Kim et al., 2021).

Despite its rich content of bioactive compounds, fiber, and nutrients, AP remains underutilized, highlighting the need for improved waste management strategies (Lyu et al., 2020; Teshome et al., 2023; Van Walraven & Stark, 2024).

Upcycling offers a promising solution by converting waste into valuable products, reducing both environmental impact and carbon emissions. This process minimizes the need for new raw materials and prevents the release of greenhouse gases from waste, thereby promoting resource efficiency and environmental conservation (Idrishi et al., 2022; Lizundia et al., 2022). Utilizing AP through upcycling and recycling is crucial for addressing the environmental and economic challenges associated with its disposal.

A example of upcycling apple by-products internationally is provided by BGG Inc., which offers ApplePfenon® as a health functional food. This product is characterized by its content of polyphenols and proanthocyanidins, exceeding 60%. Additionally, Cargill, Inc. utilizes apple by-products to produce pectin, a high-value ingredient that enhances the texture and stability of both dairy and plant-based products. Similarly, in South Korea, Four companies, Seoheung, Kolmar BNH, Unizen, and BTC, have conducted clinical trials and registered four ingredients as individually approved health functional food materials. These initiatives not only reduce waste but also increase the economic value of a by-product that would otherwise be discarded, underscoring the potential for industrial-scale upcycling to promote environmental sustainability and meet market demands.

With the expansion of the apple processing industry, the volume of AP generated is expected to rise, posing an escalating environmental challenge that current waste management practices are insufficient to address (Lohani & Muthukumarappan, 2014; Rana et al., 2021; Abdessemed et al., 2022).

This mini-review explores various sustainable applications of AP, including its conversion into animal feed, organic fertilizers, biofuels, functional food ingredients, and other high-value products such as cosmetics and pharmaceuticals. These applications can significantly reduce environmental impact, mitigate pollution, and promote ecological sustainability.

2. Characteristics and Composition of AP

AP is a byproduct of apple juice production and consists mainly of apple skin and flesh. It contains high levels of dietary fibers, vitamins, and minerals, including phenolic compounds such as catechins, procyanidins, and chlorogenic acid, which are known for their antioxidant and anti-inflammatory properties (Kauser et al., 2024). AP is also a significant source of pectin, is widely used in the food industry for its gelling properties and can be incorporated into various food formulations to enhance the dietary fiber content and overall health benefits of products, such as bakery items, dairy products, and meat substitutes (Kauser et al., 2024).

AP is abundant in dietary fibers, including insoluble fibers such as cellulose, hemicellulose, and soluble pectin, which are essential for digestive health and various food industry applications (Lyu et al., 2020; Zhao et al., 2022; Buljeta et al., 2023). The physical properties of AP include high moisture content, which makes it susceptible to microbial growth. The moisture content of AP varies depending on the apple cultivar and processing method, generally ranging from 70% to 80% (Krasnova & Segliņa, 2019; Lyu et al., 2020; Sobczak et al., 2022).

Additionally, AP has potential applications beyond food products, such as in the production of biofuels and animal feed and as a substrate for cultivating beneficial microorganisms (Iqbal et al., 2021). Optimal pretreatment and extraction technologies enable the efficient recovery of these compounds, support sustainable utilization, and reduce environmental waste (Nirmal et al., 2023).

2.1. Production volume: Domestic and international quantities

According to 2022 reports, South Korea produced approximately 566,041 tons of apples, with 46,406 tons being processed (Ministry of Agriculture, Food and Rural Affairs, 2022; Statistics Korea, 2022). This type of processing generates large amounts of AP, most of which is discarded as industrial waste (Kim et al., 2021). Proper management is necessary to avoid environmental challenges and capitalize on potential uses. Globally, the major apple-producing countries, such as China, the United States, and European nations, generate millions of tons of AP annually. China produces over four million tons, the United States approximately 1 million ton, and European countries approximately two million tons, contributing significantly to the global volume (Golebiewska et al., 2022; Manrich, 2024).

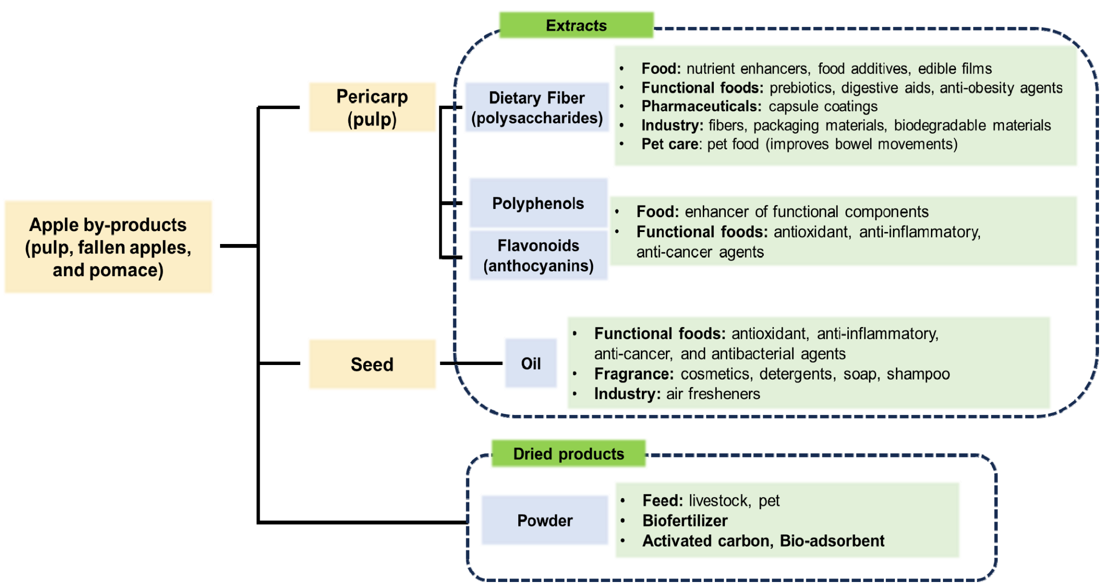

Fig. 1. Strategies for the industrial utilization of apple by-products as functional materials.

2.2. Environmental impact

The disposal and management of AP have significant environmental implications. The disposal of AP in landfills leads to anaerobic decomposition, which produces methane, a potent greenhouse gas (Czubaszek et al., 2022). Leachates from decomposing AP can contaminate soil and water, increasing ecological risks (Giamouri et al., 2023). Furthermore, current disposal practices waste valuable resources that can be repurposed for various applications, such as biofuel and biogas production. AP is a useful resource for producing biofuels and other value-added products (Duan et al., 2021; Giamouri et al., 2023).

3. Utilization of AP

AP, a byproduct of apple processing, has significant potential in various industries owing to its high fiber, polyphenol, and other bioactive compound contents. It is used in multiple applications, including animal feed, organic fertilizers, food and beverage improvement, biofuel production, pharmaceuticals, and cosmetics. Fig. 1 presents the strategies for industrial utilization of apple by-products, including AP.

The potential applications of AP can be broadly categorized into upcycling and downcycling processes. In the upcycling domain, AP is repurposed into high-value products, while in downcycling, it is converted into lower-value materials, often with reduced functionality (Fig. 2). Both processes are integral to circular economy but differ in their impact on material value and resource efficiency. These diverse applications leverage the nutritional and functional properties of AP; however, each has specific benefits and challenges.

As an alternative to landfilling, AP is partially utilized in downcycling processes, primarily as fertilizer, animal feed, and biofuel.

AP offers high fiber content and essential nutrients in animal feed that benefit livestock health and productivity. However, its variable composition and challenges in storage and preservation can affect its digestibility and overall effectiveness as feed. As an organic fertilizer, AP enhances soil health and is environmentally friendly; however, the composting process can be challenging and may lead to nutrient imbalances if not properly managed (Zhang et al., 2021; Abdessemed et al., 2022; Kauser et al., 2024).

For biofuel production, AP can be converted into bioethanol and biogas, thereby contributing to renewable energy sources. However, processing costs and variability in feedstock composition pose significant challenges (Rana et al., 2021; Golebiewska et al., 2022).

In food and beverage production, AP is valued for its ability to enhance the nutritional profile and act as a natural sweetener. Despite its benefits, concerns related to flavor, texture, regulatory approval, and shelf life need to be addressed (Lyu et al., 2020; Abdessemed et al., 2022).

In pharmaceuticals and cosmetics, the high phenolic and antioxidant contents of AP make it a valuable ingredient in health and beauty products. Nonetheless, the costs associated with extraction and regulatory hurdles, along with market acceptance, are key obstacles to its widespread use (Rana et al., 2021; Abdessemed et al., 2022).

Despite its potential, the current pretreatment process faces significant challenges during the drying phase due to the stickiness induced by polysaccharides and monosaccharides, which limits its industrial application. To enable the full utilization of AP in industrial processes, these obstacles must be addressed through

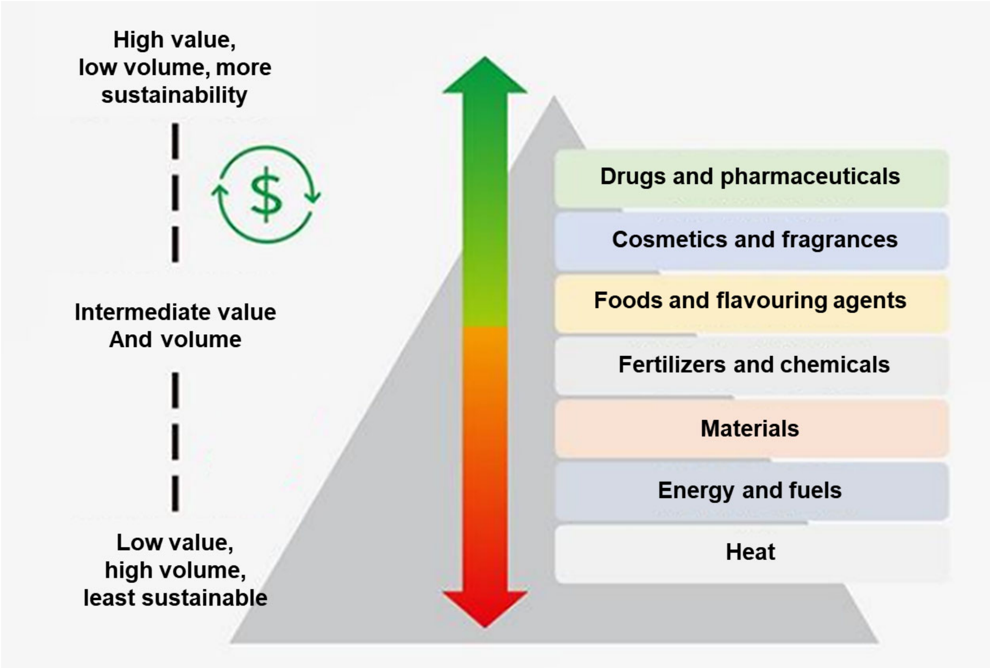

Fig. 2. Perspective towards effective utilization of fruit and vegetable waste (Source: Ganesh et al., 2022).

further research. Consequently, optimizing pretreatment technologies is essential for the effective upcycling of AP and its successful adoption in industrial applications.

4. Recent Research Trends

Recent studies have highlighted the significant potential of AP in various industrial applications. Research in South Korea has focused on incorporating AP into bakery products to enhance their nutritional profiles and antioxidant capacities. For instance, the addition of AP to bakery products can significantly increase their phenolic content, contributing to improved antioxidant properties and health benefits (Lyu et al., 2020; Abdessemed et al., 2022). In addition, dried AP has been used in animal feed to improve nutrient intake and livestock health, demonstrating notable improvements in the nutritional quality of meat products when used as a feed supplement (Lyu et al., 2020).

Furthermore, AP composting has been shown to enhance soil fertility and crop yield by improving soil structure and nutrient content (Rana et al., 2021; Chaudhary et al., 2024). Internationally, notable research has included the use of pretreated AP in anaerobic digestion to increase methane production for bioenergy, indicating its potential as a renewable energy source (Antonic et al., 2020). In the pharmaceutical and cosmetic industries, phenolic compounds extracted from AP have demonstrated antioxidant and anti-inflammatory properties, highlighting their potential use in the development of health-promoting products (Putra et al., 2023).

Moreover, AP has been utilized as a food additive to create high-fiber snacks and beverages, which enhance their nutritional value

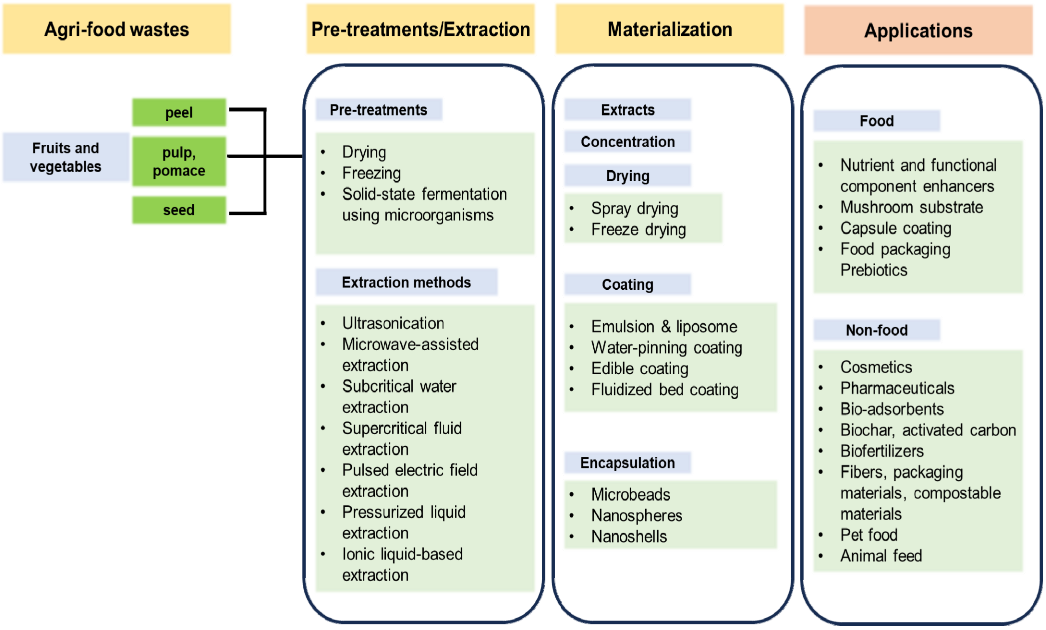

Fig. 3. System for pre-treatment, extraction, and materialization of fruit and vegetable by-products.

and offer functional health benefits (Rana et al., 2021; Kauser et al., 2024). These studies suggest that AP is a versatile resource that can achieve both environmental sustainability and economic benefits, underscoring its potential for widespread application in different sectors.

5. Challenges and Future Directions

The valorization of AP presents significant potential; however, various technical, economic, and environmental challenges remain. Overcoming these challenges in the utilization of agri-food wastes such as AP requires a integrated approach, as shown in Fig. 3.

First, One key scientific and technological challenge is the efficient extraction and utilization of bioactive compounds from AP using green technologies, such as supercritical CO_2 extraction and ultrasonic-assisted extraction. These techniques, although promising, often require significant capital investment and optimization for scalability, which can be a barrier for industrial adoption. Furthermore, ensuring the stability and functionality of extracted compounds during storage and incorporation into food, cosmetic, or pharmaceutical products remains a critical hurdle.

Second, from an economic perspective, the processing costs associated with AP can make final products more expensive than conventional alternatives, thereby weakening market competitiveness. Moreover, consumer awareness and acceptance of AP-derived products derived from AP. Therefore, consumer education and promotional campaigns are necessary to improve market development. Attracting investment in a large-scale processing infrastructure requires significant capital, and collaboration between the government and private sectors is essential for building the necessary infrastructure and providing financial support.

Third, from an environmental perspective, although the valorization of AP reduces waste and mitigates environmental stress, the processes involved may still generate by-products or require the use of energy and water resources. Thus, integrating sustainability into the entire valorization process, from extraction to end-use applications, is essential. This could involve utilizing renewable energy sources or adopting circular economy principles where waste streams are minimized or reused within the system.

Addressing these challenges will unlock the potential of AP, transform it from a waste product into a valuable resource, and benefit both the economy and the environment.

6. Conclusion

This review highlights the substantial potential of AP as a valuable resource, emphasizing its rich content of dietary fiber, phenolic compounds, vitamins, and minerals, making it suitable for various applications in animal feed, organic fertilizers, food additives, biofuels, and pharmaceutical and cosmetic industries. With significant domestic and global production volumes, effective management and sustainable utilization of AP can mitigate environmental challenges such as greenhouse gas emissions and soil and water pollution. By transforming AP from waste into a valuable resource, we can contribute to a circular economy and reduce the environmental footprint of the apple-processing industry. Further research to standardize and optimize AP utilization is crucial for maximizing its potential and advancing toward a sustainable future.

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