

VALORIZATION OF BIOACTIVE COMPOUNDS FROM AONLA PROCESSING RESIDUES FOR PHARMACEUTICAL APPLICATIONS

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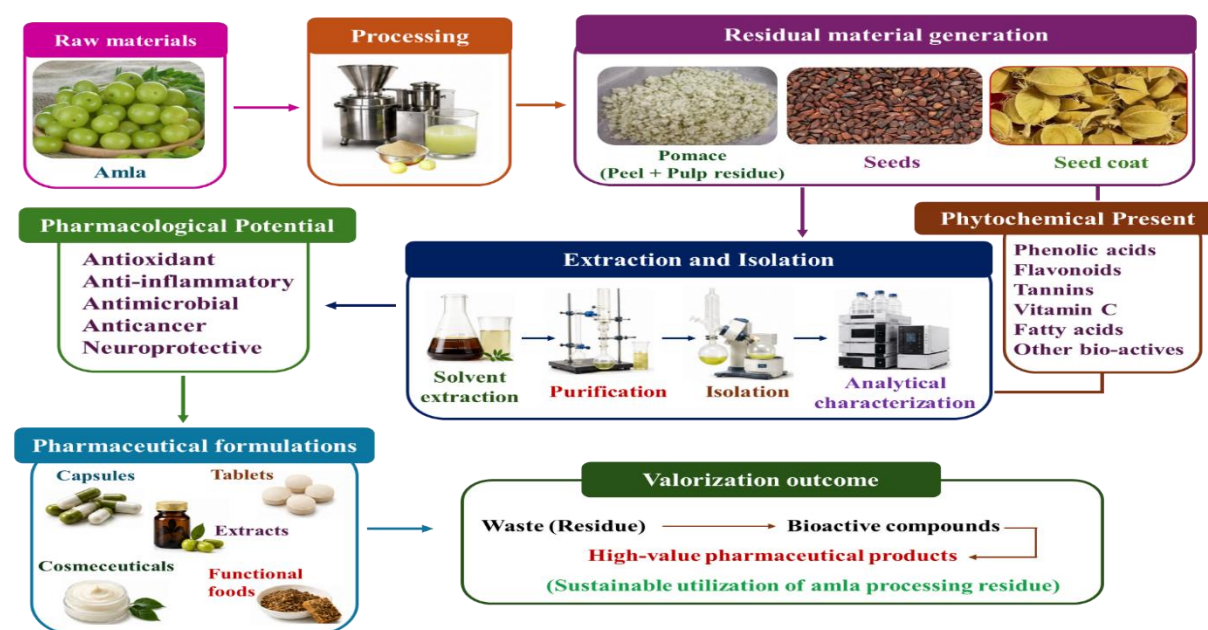
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1. ABSTRACT

Aonla (*Phyllanthus emblica* L.) processing generates substantial residues particularly pomace, seeds and seed coats, which are often underutilized despite their rich bioactive composition. These residues contain phenolics, flavonoids, tannins, fatty acids and dietary fibre associated with antioxidant, antimicrobial, anti-inflammatory and other pharmacological properties. This review summarizes the generation, phytochemical composition, extraction, characterization and pharmaceutical potential of bioactive compounds from aonla processing residues. Recent studies demonstrate considerable antioxidant activity and the presence of valuable phenolic and flavonoid compounds in pomace, seeds and seed coats, while advanced extraction, purification and delivery approaches enhance their utilization potential. Emerging pharmaceutical applications include liposomal systems, herbal formulations and nanocomposite-based delivery systems. The valorization of these residues also supports waste reduction, resource efficiency and circular economy development. However, variability in residue composition, limited in-vivo and clinical evidence, safety concerns, bioavailability, scalability and lack of standardized processes remain key challenges. Future research should focus on standardized extraction, detailed phytochemical characterization, safety and bioavailability evaluation, pharmacokinetic studies, clinical validation and techno-economic assessment to enable the sustainable conversion of aonla processing residues into high-value pharmaceutical and nutraceutical products.

KEYWORDS: Aonla, Processing residues, Phytochemicals, Pharmaceutical applications, Valorization

GRAPHICAL ABSTRACT



2. INTRODUCTION

The modern pharmaceutical industry is increasingly exploring plant-derived bioactive compounds as natural and sustainable sources of therapeutic agents. Plant secondary metabolites including phenolics, flavonoids, tannins, alkaloids, terpenoids, saponins and glycosides, exhibit diverse pharmacological activities such as antioxidant, anti-inflammatory, antimicrobial, antiviral, antidiabetic, hepatoprotective, neuroprotective and anticancer effects (Atanasov *et al.*, 2021; Newman & Cragg, 2020). Their structural diversity and multi-target activities make them promising candidates for developing novel therapeutics (Dias *et al.*, 2012).

Among medicinally important plant resources, aonla (*Phyllanthus emblica* L.) has gained significant scientific interest due to its rich phytochemical composition and it has been widely used in traditional systems of medicine, particularly Ayurveda (Variya *et al.*, 2016). Based on pharmacological studies, aonla has antioxidant (Sheoran *et al.*, 2019), immunomodulatory (Jantan *et al.*, 2019), anticancer (Chekdaengphanao *et al.*, 2022; Mahata *et al.*, 2013), cytoprotective (Zhang *et al.*, 2016), anti-viral (Lv *et al.*, 2014), nephroprotective (Huang *et al.*, 2023), antiaging (Wu *et al.*, 2022), anti-jaundice, anti-dyslipidemic (Quranayati *et al.*, 2023) anti-inflammatory (Wang *et al.*, 2019) and anti-diabetic (Naik & David, 2023).

The increasing demand for aonla-based products has led to its processing into a variety of value-added products including juice, beverages, candy, preserves, powder and other processed products. These processing operations generate residual materials, particularly pomace, seeds and their fractions, which are often underutilized or discarded. However, these residues can preserve significant amounts of valuable phytochemicals, dietary fibre and other functional compounds, offering opportunities for waste reduction and sustainable bioactive recovery (Lankanayaka *et al.*, 2024).

Among the residues generated during aonla processing, aonla pomace is particularly important as it retains valuable phytochemicals, polyphenols, dietary fibre and other functional constituents after juice extraction, making it a promising substrate for the recovery of bioactive compounds. Macroporous resin purification enhanced the polyphenol content and antioxidant activity of *Phyllanthus emblica* pomace extract and that purified extract showed potential anti-Alzheimer's activity in a transgenic *Caenorhabditis elegans* (nematode) model (Gan *et al.*, 2022). Similarly, aonla seeds and seed coats contain diverse phytochemicals including phenolics, flavonoids, tannins, terpenoids and phytosterols, with seed extracts showing antioxidant, antimicrobial and concentration-dependent cytotoxic activities, indicating their potential for further pharmacological investigation (Subbiah U, 2025). However, aonla seeds remain less studied than the fruit, particularly for phytochemical characterization, extraction optimization, safety and pharmaceutical applications. Thus, valorization of aonla processing residues offer a sustainable approach for recovering valuable bioactive, reducing processing waste and supporting pharmaceutical and nutraceutical applications.

3. RESIDUAL GENERATION AND PROCESSING STREAMS

Depending on the final product and processing technique, aonla processing generates various residual streams. Juice and beverage processing mainly produces aonla pomace, which contains residual pulp, peel, cellular materials and other insoluble components remaining after juice extraction. In contrast, processing operations involving fruit cutting, deseeding and seed removal generate seeds and their fractions as distinct residues. Differences in chemical composition require stream-specific valorization approaches.

Aonla pomace is considered a promising processing residue because it retains appreciable levels of bioactive compounds including polyphenols and other phytochemicals, after juice extraction. Resin purification and ultrasound-assisted subcritical water extraction improved polyphenol recovery and antioxidant activity, while liposomal encapsulation enhanced extract stability (Gan *et al.*, 2022). These findings support its pharmaceutical use as a source of purified bioactive ingredients for advanced delivery systems.

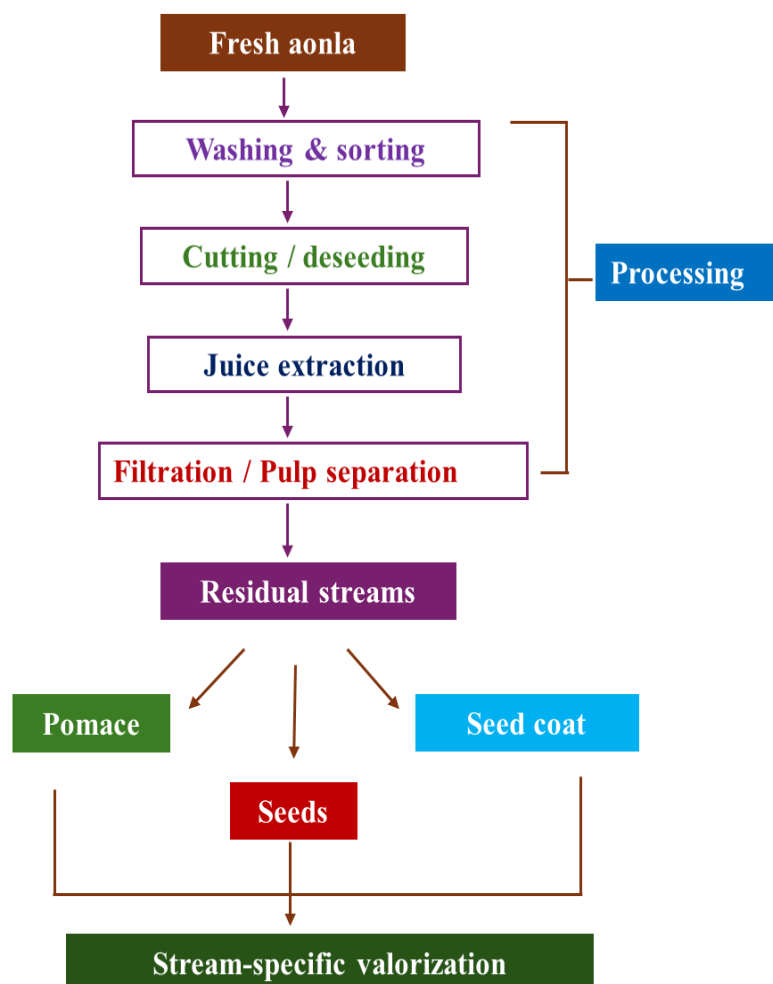
Aonla seeds and their individual fractions represent valuable but comparatively underexplored residues of aonla processing. Based on the separation and processing operations employed, the seed material can be further classified into distinct fractions, such as the seed coat and internal seed components. Each fraction may vary in its phytochemical composition and consequently, in its functional properties and pharmaceutical applications.

Aonla seeds are comparatively underexplored but contain phenolics, flavonoids, tannins and fatty acids that are associated with antioxidant, antibacterial and anti-inflammatory activities. The yellowish-brown seeds of aonla contain stearic acid, linoleic acid, palmitic acid, linolenic acid, myristic acid and oleic acid while D-myoinositol, D-glucose and D-fructose are predominantly identified in the ethanol fractions of aonla (Saini *et al.*, 2022). Aonla seed extracts exhibited antioxidant, antibacterial and anti-inflammatory activities, with different solvent fractions showing varying bioactivities (Singh *et al.*, 2022). These findings suggest that aonla seeds should be considered not merely as processing waste but as a potential source of bioactive compounds for pharmaceutical and other applications. Among the seed fractions, the seed coat has received particular attention because of its phytochemical and mineral composition. Several phenolic compounds, including gallic acid, catechin, caffeic acid, quercetin, p-coumaric acid, vanillic acid and chlorogenic acid were identified in aonla seed coat, while the ethyl acetate fraction exhibited 61.07% DPPH radical-scavenging activity (Mishra *et al.*, 2015). The overall valorization pathway of aonla processing residues including the recovery of bioactive compounds and their potential pharmaceutical applications, is illustrated in Figure 1.

Figure 1. Valorization pathway of bioactive compounds from aonla processing residues for pharmaceutical applications

4. BIOACTIVE COMPOSITION AND PHARMACOLOGICAL POTENTIAL OF AONLA

RESIDUAL GENERATION & PROCESSING STREAMS



PROCESSING RESIDUES

Aonla processing residues particularly pomace, seeds and seed coat contain diverse bioactive compounds including phenolic acids, flavonoids, tannins and fatty acids, which exhibit antioxidant, antimicrobial and anti-inflammatory activities, highlighting their potential for pharmaceutical valorization.

4.1. POMACE

4.1.1. Antioxidant activity

Aonla pomace is a rich source of antioxidant compounds particularly polyphenols, tannins and ascorbic acid. Aonla pomace powder contains substantial dietary fibre (41.7 g100 g⁻¹), ascorbic acid (432 mg100 g⁻¹), tannins (524 mg100 g⁻¹) and polyphenols (677 mg100 g⁻¹) (Raju *et al.*, 2025). Further, Aonla pomace powder exhibited strong antioxidant activity with 67.42% DPPH radical scavenging, 86.21% 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) inhibition and 1584.99 µmol ascorbic acid equivalent (AAE)g⁻¹ dry weight (DW) ferric-reducing power (Muzaffar *et al.*, 2023). In addition, Aonla pomace retained considerable phenolic and flavonoid contents and exhibited DPPH radical-scavenging activity, with the highest values observed at 60°C, indicating its potential as a source of antioxidant bioactives (Fatima & Kumar, 2026). Beyond its antioxidant properties, aonla pomace-derived polyphenols have demonstrated promising pharmacological potential.

4.1.2. Antibacterial activity

Aonla pomace also exhibits antibacterial potential (Krishna & Prasad, 2024). The presence of phenolic compounds, flavonoids and tannins may contribute to its antimicrobial properties, supporting its potential application as a natural bioactive ingredient for functional and nutraceutical applications.

4.1.3. Prebiotic activity

Aonla pomace possesses promising prebiotic potential due to its dietary fibre and diverse polysaccharides. Aonla pomace contains 41.7 g100 g⁻¹ dietary fibre (Raju *et al.*, 2025), along with 17.85% dietary fibre along with galactose, galacturonic acid, arabinose, rhamnose, glucose, xylose and mannose (Fatima & Kumar, 2025). In addition, aonla pomace flour (APF) contained 55.83% dietary fibre, while in vitro gastrointestinal digestion resulted in 81% phenolic and 84% flavonoid bioaccessibility, accompanied by enhanced antioxidant capacity (Mall & Patel, 2025). APF also promoted *Lactobacillus acidophilus* proliferation and increased propionate and butyrate production during fermentation, indicating promising prebiotic potential.

4.1.4. Nutritional and functional potential

In addition to bioactive compounds, aonla pomace contains substantial dietary fibre and ascorbic acid, supporting its use in functional foods and nutraceuticals. The enhanced bioaccessibility of phenolics and flavonoids after digestion further indicates its potential for delivering bioactive compounds through food-based applications.

4.2. SEEDS

4.2.1. Antioxidant activity

Aonla seeds contain diverse phenolic acids and flavonoid compounds, including caffeic acid, coumaric acid, syringic acid, tannic acid and myricetin. The seeds exhibited appreciable antioxidant activity along with high tannin content (Nambiar *et al.*, 2015). In addition, aonla seed extract contained high levels of tannins (126.71 mg tannic acid equivalents [TAE] g⁻¹) and flavonoids (1016.25 mg quercetin equivalents [QE] g⁻¹), indicating its potential as a source of bioactive compounds (Sriwatcharakul, 2020).

4.2.2. Antibacterial and Anti-inflammatory Activities

Aonla seed extracts exhibit both antibacterial and anti-inflammatory potential. Methanolic seed extract showed antibacterial activity against *Escherichia coli*, *Proteus vulgaris* and *Klebsiella pneumoniae*, along with 15-lipoxygenase inhibitory activity at concentrations of 5-25 µg, highlighting the potential of seed-derived bioactives as natural antimicrobial and anti-inflammatory agents (Singh *et al.*, 2022).

4.2.3. Bioactive fatty acid and anti-biofilm potential

Aonla seeds are also a source of bioactive fatty acids. Aonla seed oil obtained by supercritical carbon dioxide (CO₂) extraction was enriched in linolenic acid (~20% w/w), highlighting the potential of aonla seeds as a source of bioactive fatty acids with antimicrobial and anti-biofilm potential (Balkrishna, Ngpooreb, *et al.*, 2025).

4.2.4. Phytochemical composition

The seeds contain alkaloids, phytosterols, phenols, flavonoids, tannins and proteins with octyl-β-D-glucopyranoside identified as a major compound by Gas Chromatography-Mass Spectrometry (GC-MS) analysis (Dinesh *et al.*, 2016). The biological activities of these compounds further enhance the pharmaceutical relevance of aonla seeds. Thus, aonla seeds represent a promising source of multifunctional bioactives with antioxidant, antimicrobial and anti-inflammatory potential.

4.3. SEED COAT

4.3.1. Antioxidant activity

Aonla seed coat is particularly rich in phenolic compounds and flavonoids and exhibits strong antioxidant activity. Aonla seed coat extract was rich in phenolics (439.09 ± 5.49 mg GAE g⁻¹ extract) and exhibited strong antioxidant activity (FRAP: 751.92 ± 5.22 mg AAE g⁻¹ extract) (Jaiboonma *et al.*, 2018). Additionally, aonla seed coat contains phenolics and flavonoids with total phenolic content of 12.81 mg gallic acid equivalents (GAE) g⁻¹ DW and total flavonoid content of 10.37 mg quercetin equivalents (QE) g⁻¹ DW (Kaur *et al.*, 2021). Consistent with these findings, aonla seed coat showed DPPH radical-scavenging activity comparable to fruit powder, while seed powder exhibited approximately 30% DPPH radical-scavenging activity (Mishra & Mahanta, 2014).

4.3.2. Pharmacologically relevant phenolic constituents

Several important phenolic compounds, including gallic acid, catechin, caffeic acid, quercetin, p-coumaric acid, vanillic acid and chlorogenic acid were identified in aonla seed coat, strengthening its potential as a concentrated source of pharmaceutical bioactives (Mishra *et al.*, 2015). Furthermore, butanol extracts of aonla seed coat exhibited antibacterial and antifungal activities with antifungal inhibition against *Fusarium oxysporum* increasing with extract concentration (Kaur *et al.*, 2021). These findings indicate that the phenolic-rich seed coat may contribute to multiple biological activities beyond antioxidant effects.

4.3.3. Pharmaceutical potential

The high phenolic and flavonoid content, together with antioxidant and antimicrobial activities highlight aonla seed coat as a potential source of multifunctional pharmaceutical bioactives. Its ability to provide multiple bioactivities from a processing residue supports its valorization as a natural antioxidant and antimicrobial ingredient for pharmaceutical and related biomedical applications.

The reported findings indicate that aonla processing residues possess diverse bioactive constituents with distinct biological activities. A comparative summary of the major bioactive constituents, biological activities and key findings reported for pomace, seeds and seed coat is presented in Table 1.

Table 1. Comparative overview of bioactive constituents and pharmacological potential of aonla processing residues

Residue	Bioactive constituents	Biological activity	Key findings	References
Pomace	Gallic acid, 1-O-galloyl-β-D-glucose, corilagin	Antibacterial	Phenolic compounds isolated from aonla pomace exhibited antibacterial activity against <i>Streptomyces scabies</i> .	(Wu <i>et al.</i> , 2024)
Seed	Fatty acids, non-polar and unsaponifiable phytochemicals	Antimicrobial, anti-biofilm	Supercritical CO ₂ -extracted seed oil showed bactericidal and anti-biofilm activity; linolenic acid was the major PUFA (33.5%).	(Balkrishna, Maheswari, <i>et al.</i> , 2025)
	Linolenic acid-rich oil	Quorum-quenching, anti-biofilm, anti-infective	Seed oil inhibited <i>Pseudomonas aeruginosa</i> growth, motility and virulence-factor secretion and showed activity in a <i>C. elegans</i> infection model.	(Balkrishna, Ngpooreb, <i>et al.</i> , 2025)
	Gallic acid, vanillic acid, sinapic acid, p-coumaric acid, ellagic acid, myricetin, quercetin	Antioxidant, antimicrobial	Ethyl-acetate seed extract showed antioxidant activity and was incorporated into bakery products to improve oxidative stability and shelf life.	(Lankanayaka <i>et al.</i> , 2026)
Seed coat	Phenolics, gallic acid, fatty acids	Antioxidant and functional properties	Seed coat showed the second highest DPPH scavenging activity after fruit and exhibited higher water-retention and swelling capacities than seed powder.	(Mishra & Mahanta, 2014)

5. EXTRACTION, ISOLATION AND CHARACTERIZATION OF BIOACTIVE COMPOUNDS

Different extraction and analytical approaches have been employed to recover and characterize bioactive compounds from aonla processing residues, as summarized in Table 2.

Table 2. Extraction, isolation and characterization methods used for bioactive compounds from aonla processing residues

Residues	Extraction/ Isolation	Characterization/ Analysis	Reference
Pomace	Macroporous resin (NKA-II) purification; 70% aqueous ethanol used as eluent	Polyphenol composition and antioxidant activity; chromatographic analysis	(Gan <i>et al.</i> , 2022)
	70% ethanol extraction using a shaking water bath at 35 °C for 8 hours	Total polyphenols, flavonoids, DPPH, ABTS and ferric-reducing antioxidant activity	(Muzaffar <i>et al.</i> , 2023)
Seed	Solvent extraction	Phytochemical screening, GC-MS analysis, total tannin and flavonoid estimation	(Dinesh <i>et al.</i> , 2016; Sriwatcharakul, 2020)
Seed Coat	Maceration, orbital shaking, ultrasonication assisted and Soxhlet extraction	Total phenolic content, total flavonoid content, antioxidant, antibacterial and antifungal activities	(Kaur <i>et al.</i> , 2021)

6. PHARMACEUTICAL FORMULATION AND DELIVERY

The pharmaceutical utilization of aonla processing residues requires suitable formulation and delivery systems to overcome limitations such as poor stability, low bioavailability, oxidation and limited solubility of phytochemicals. Encapsulation and nanoscale delivery systems can protect sensitive bioactive compounds, improve their stability and facilitate controlled or sustained release.

An integrated ultrasound-assisted subcritical water extraction and liposomal encapsulation strategy was developed for polyphenols recovered from aonla pomace. The resulting polyphenol-loaded liposomes showed an encapsulation efficiency of $83.07 \pm 0.09\%$, retained structural integrity after four weeks at 4°C and exhibited stronger antioxidant activity than the free extract (Liang *et al.*, 2025). This study provides evidence for converting an aonla processing residue-derived extract into a stabilized bioactive delivery system with potential pharmaceutical applications. Similarly, aonla seed extract was successfully incorporated into an oral herbal suspension containing aqueous seed extract with sodium carboxymethyl cellulose, Tween 80 and other excipients.

The optimized extract showed 59.56% inhibition of H⁺/K⁺-ATPase at 100 µg/mL, compared with 66.98% for omeprazole, indicating potential anti-ulcer activity (Jain *et al.*, 2025). For topical applications, silver-zinc oxide (Ag/ZnO) nanocomposites were developed using aonla seed extract as a reducing and stabilizing agent. The nanocomposites demonstrated antibacterial, antioxidant, anti-inflammatory and wound-healing activities, highlighting the potential of seed-derived phytochemicals in nanostructured wound-care formulations (Vidhyadevi & Suseem, 2026). In addition to improving stability, such delivery platforms may enhance the solubility, bioavailability and controlled release of residue-derived phytochemicals, thereby increasing their functional performance. However, parameters such as particle size, encapsulation efficiency, active-compound loading, release kinetics and storage stability require systematic optimization for formulation standardization. Overall, liposomal, suspension and nanocomposite-based systems offer promising approaches for utilizing bioactive compounds from aonla processing residues in pharmaceutical applications. However, further studies are needed to establish their bioavailability, safety, stability, pharmacokinetics and in-vivo efficacy before pharmaceutical translation.

7. CIRCULAR ECONOMY AND SUSTAINABILITY PERSPECTIVE

Valorization of aonla processing residue provides an opportunity to establish a cascade utilization strategy, where pomace, seeds and seed coats are sequentially converted into high-value products. These residues can be utilized for recovering polyphenols, phenolic acids, flavonoids, fatty acids, dietary fibre and other functional components, thereby reducing organic waste and improving resource efficiency. The use of green extraction technologies including ultrasound-assisted, microwave-assisted and enzyme-assisted extraction can further improve the sustainability of bioactive recovery by reducing solvent consumption, processing time and energy requirements. Following extraction, residual biomass may be utilized as fibre-rich ingredients, fermentation substrates or other biomaterials, promoting maximum resource recovery. From an economic perspective, converting aonla residues into functional ingredients, nutraceuticals, pharmaceutical formulations and cosmetic products can create additional revenue streams for processing industries while reducing waste-management costs. This approach supports both value creation and sustainable utilization of agricultural resources. A biorefinery-based approach integrating extraction, purification, formulation and residual biomass utilization could further strengthen the circular bioeconomy of aonla processing. Future studies should emphasize life-cycle assessment, techno-economic feasibility, process scalability, safety and regulatory validation to facilitate industrial adoption.

8. CHALLENGES AND RESEARCH GAPS

Despite the promising evidence, several challenges need to be addressed before aonla processing residues can be developed into standardized pharmaceutical raw materials. The chemical composition of residues may vary with cultivar, maturity, geographical origin and processing conditions, highlighting the need for standardized raw-material specifications. In addition, extraction conditions strongly influence the recovery of phenolic and flavonoid compounds, making optimization and process standardization essential. Most available evidence is still based on in-vitro or preliminary in-vivo studies, such as the anti-Alzheimer's activity of pomace polyphenols in *C. elegans* and the biological evaluation of seed-derived nanocomposites using bacterial and fibroblast cell models. Therefore, mammalian studies, pharmacokinetic investigations and clinical validation are required to confirm their therapeutic efficacy. Safety and toxicity also require greater attention, particularly for nanostructured formulations along with evaluation of long-term stability and scalability. Future research should therefore move beyond total phenolic content and antioxidant activity toward identification of individual bioactive compounds, elucidation of molecular mechanisms, bioavailability, pharmacokinetics and development of standardized pharmaceutical formulations. Future research should focus on establishing residue-specific chemical markers and standardized quality-control parameters for aonla processing residues. Although numerous phenolic compounds, flavonoids, tannins and fatty acids have been reported, differences in cultivar, maturity, processing conditions and extraction procedures can influence their concentration and biological activity. Therefore, standardized marker-based characterization, validated extraction protocols and batch-to-batch quality assessment are required to improve the reproducibility of bioactive extracts. In addition, greater emphasis should be placed on correlating individual compounds with specific pharmacological mechanisms rather than relying mainly on total phenolic content and general antioxidant assays. Such standardization would facilitate the translation of aonla residue-derived bioactives from laboratory studies toward reproducible pharmaceutical applications.

9. CONCLUSION

Aonla processing residues, particularly pomace, seeds and seed coats, represent valuable sources of bioactive compounds with pharmaceutical potential. Their valorization can convert low-value processing residues into valuable sources of antioxidant, antimicrobial, anti-inflammatory, antidiabetic and other pharmacologically relevant compounds while simultaneously reducing agro-industrial waste. Integration of green extraction, advanced characterization and pharmaceutical formulation can facilitate their development into potential pharmaceutical and nutraceutical applications. However, standardized phytochemical characterization, extraction, safety, bioavailability, clinical and techno-economic studies are needed for practical application. Thus, systematic valorization of aonla processing residues offers a promising pathway toward sustainable resource utilization, circular economy and pharmaceutical innovation.

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