

IMPROVING THE TECHNOLOGY OF POLYPHENOL RECOVERY AND ANTIOXIDANT FUNCTIONAL INGREDIENT PRODUCTION IN THE COMPLEX PROCESSING OF POMEGRANATE (PUNICA GRANATUM L.): A REVIEW

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Abstract. Pomegranate processing generates large peel and seed by-products rich in polyphenols (mainly punicalagin and ellagic acid) and punicalic acid. This review summarises the composition of these by-products, compares technologies for polyphenol recovery from the peel (ultrasound-, microwave-, pressurised-liquid-, enzyme-, electrotechnology- and deep-eutectic-solvent-assisted extraction), and describes routes to antioxidant functional ingredients, including encapsulation. Green intensified methods shorten extraction time and raise yields compared with conventional solvent extraction. An integrated cascade of seed-oil recovery, peel extraction, purification, stabilisation and fibre use is proposed; pilot-scale validation and standardised comparison remain the key gaps.

Keywords: pomegranate peel; polyphenols; punicalagin; green extraction; antioxidants; functional ingredients.

Annotatsiya. Anorni qayta ishlashda po'choq va urug'dan iborat ko'p miqdordagi ikkilamchi mahsulotlar hosil bo'ladi. Ular polifenollarga (asosan punikalagin va ellag kislotasi) hamda punik kislotaga boy. Ushbu sharhda bu mahsulotlarning tarkibi umumlashtirilgan, po'choqdan polifenollarni ajratib olish texnologiyalari (ultratovush, mikroto'lqin, bosim ostidagi suyuqlik, fermentativ, elektrotexnologiyalar va chuqur evtektik erituvchilar yordamidagi ekstraksiya) solishtirilgan hamda antioksidant xususiyatli funksional ingredientlar olish yo'llari, jumladan kapsulalash tavsiflangan. Intensivlashtirilgan «yashil» usullar an'anaviy erituvchili ekstraksiyaga nisbatan ekstraksiya vaqtini qisqartiradi va unumni oshiradi. Urug' moyini ajratish, po'choq ekstraksiyasi, tozalash, stabillash va oziq tolalaridan foydalanishni o'z ichiga olgan kompleks kaskad sxema taklif etilgan. Asosiy bo'shliqlar: pilot miqyosda tekshirish va usullarni standartlashtirilgan solishtirish.

Kalit so'zlar: anor po'chog'i; polifenollar; punikalagin; «yashil» ekstraksiya; antioksidantlar; funksional ingredientlar.

Аннотация. При переработке граната образуются крупные потоки вторичных продуктов (кожура и семена), богатые полифенолами (главным образом пуникалагином и эллаговой кислотой) и пуниковой кислотой. В обзоре обобщён состав этих побочных продуктов, сопоставлены технологии извлечения полифенолов из кожуры (ультразвуковая, микроволновая, экстракция под давлением, ферментативная, с использованием электротехнологий и глубоких эвтектических растворителей) и описаны пути получения функциональных ингредиентов с антиоксидантными свойствами, включая инкапсулирование. Интенсифицированные «зелёные» методы сокращают время экстракции и повышают выход по сравнению с традиционной экстракцией растворителями.

Предложена комплексная каскадная схема: выделение масла из семян, экстракция кожуры, очистка, стабилизация и использование пищевых волокон. Ключевые пробелы: плотная валидация и стандартизированное сравнение методов.

Ключевые слова: *кожура граната; полифенолы; пуникалагин; «зелёная» экстракция; антиоксиданты; функциональные ингредиенты.*

INTRODUCTION. Pomegranate (*Punica granatum* L.) is widely grown and processed into juice, and the solid residue left after juicing contains useful bioactive components: hydrolysable tannins (punicalagin, ellagic acid), flavonoids such as anthocyanins, and fatty acids such as punicic acid [1]. By fruit weight, the peel makes up about 43%, seeds 11% and juice 46% [2]; the peel accounts for 40–50% of the waste from juice production. Left untreated, such phenol-rich waste is also an environmental problem because of its phytotoxic potential [3].

The peel is regarded as a rich reservoir of antioxidants, polyphenols, dietary fibre and vitamins, with reported anti-inflammatory, cardioprotective, wound-healing, anticancer and antimicrobial properties attributed to gallic acid, ellagic acid and punicalagin [4]. Punicalagin makes up the majority of peel polyphenols [5], and the peel contains more of these compounds than other fruit parts [6]. Regional analyses are consistent with this: a study of peel from Uzbekistan reported a tannin content of about 5.5%, all essential amino acids, and pectin-containing polysaccharides, supporting its use as a functional ingredient [7].

Several reviews cover peel extraction [3–5], by-product use in food and cosmetics [1] and peel as a food additive [2]. However, few connect extraction technology with purification, stabilisation and the processing of all by-product fractions into one technological scheme. The aim of this review is therefore to (i) summarise the composition of pomegranate by-products, (ii) compare technologies for polyphenol recovery, (iii) describe the forms and applications of antioxidant ingredients, and (iv) propose directions for improving complex processing.

METHODS. This is a narrative review. Peer-reviewed articles (original studies and reviews) on pomegranate peel and seed valorisation, polyphenol extraction, purification, encapsulation and food applications were selected from major publisher and indexing platforms (MDPI, Royal Society of Chemistry, Elsevier, Wiley, PubMed Central). Priority was given to recent comprehensive reviews, from which primary studies were traced and checked. Articles were included if they reported extraction conditions or yields, antioxidant activity, or food/functional applications of pomegranate by-products; non-peer-reviewed web content, commercial pages and sources without bibliographic data were excluded. Because experimental designs differ (cultivar, solvent, assay standard), numerical results were compared qualitatively and are reported as stated in the cited sources; no meta-analysis was performed.

RESULTS. Peel phenolics are reported to be roughly ten times more concentrated than in pulp (249.4 versus 24.4 mg/g). Peel polyphenols comprise phenolic acids (gallic, ellagic), flavonoids and hydrolysable tannins (punicalin, punicalagin) [3]; punicalagin can account for up to 70% of peel polyphenols [5]. Peel also provides dietary fibre and minerals [4, 7]. Seeds are the second stream: their oil is dominated by punicic acid, which underlies cosmetic and nutraceutical uses, and the seeds also serve as a fibre source [1]. Concentrations vary with cultivar and growing conditions [3], which affects process standardisation.

Conventional extraction. Maceration and stirring with water, methanol, ethanol or acetone are simple and widely used, and solvent extraction gives high total phenolic content, but it is time-consuming, energy-intensive and has low cell-wall disruption [3, 5].

Water can act as an efficient green solvent: aqueous extraction of pomegranate marc gave 229 mg TAE/g within 2 min.

Ultrasound-assisted extraction (UAE). Cavitation disrupts cell walls and improves mass transfer. Continuous and pulsed UAE increased antioxidant yield by about 24% and 22% and shortened extraction time by about 90% and 87% compared with conventional extraction.

Microwave-assisted extraction (MAE). In a direct comparison, MAE was more effective than UAE, giving 199.4 mg GAE/g dry peel after 4 min, with radical-scavenging activity of about 95% for both optimised methods. A vacuum microwave aqueous process in an industrial-type extractor reached 137.97 mg GAE/g in 10 min and shows that scale-up is feasible.

Pressurised liquid and subcritical water extraction. Hot pressurised water extracted peel hydrolysable tannins at 262.7 mg/g tannic acid equivalents and punicalagin at 116.6 mg/g dry matter, with particle size, temperature and static time as the main factors. An instant controlled pressure drop pre-treatment raised phenolics from 38.77 to 46.02 mg GAE/g dry material.

Pulsed electric field (PEF) and high-voltage electrical discharge (HVED). HVED recovered polyphenols about 3 times more effectively than UAE and about 1.3 times more than PEF, while PEF selectively enhanced ellagic acid and HVED gallic acid.

Enzyme-assisted and supercritical methods. Enzyme-assisted solvent extraction gives the highest yield among advanced polyphenol methods [5]; enzyme-assisted supercritical CO₂ extraction was reported to double the recovery of crude extract and improve radical-scavenging capacity.

Deep eutectic solvents (DES). Combining DES with infrared heating gave the highest polyphenol concentration (152 mg/g dry matter) among the compared methods, whereas in another study pressurised liquids produced extracts with higher antioxidant activity than DES.

Table 1. Summary of reported performance of extraction technologies for pomegranate peel (values as reported; not directly comparable).

Technology	Reported outcome	Main limitation
Maceration / stirring	High phenolics with organic solvents; water usable	Long time, energy, low cell disruption
UAE	+22–24% antioxidant yield; –87–90% time	Lab-scale data dominate
MAE / vacuum MAE	199.4 mg GAE/g (4 min); 137.97 mg GAE/g (10 min, industrial-type)	Thermal control of sensitive compounds
PLE / subcritical water	Punicalagin 116.6 mg/g DM	Equipment cost
PEF / HVED	HVED $\approx 3\times$ UAE; PEF selective for ellagic acid	Limited industrial data
EAE / EASC-CO ₂	Highest yield among advanced methods; crude extract doubled	Enzyme cost, optimisation
DES + infrared	152 mg/g DM	Solvent recovery, safety evaluation

For isolating punicalagin from crude polyphenol extracts, liquid chromatography is the most widely used purification approach, and semi-preparative HPLC achieves the highest purity

[5]. For food use, crude or partially purified extracts are often sufficient. A process combining ultrasound-assisted extraction with encapsulation has been proposed to turn peel into a stable food ingredient. Peel powders, liquid extracts and encapsulated forms have been incorporated into several food matrices to improve shelf life, nutritional value and sensory properties [4], including functionalised meat products.

Peel extracts show high radical-scavenging activity (about 95% in optimised MAE and UAE extracts), and peel extract was found to be more antioxidant than pulp extract. Beyond antioxidant action, *in vitro* antimicrobial, anticancer and antiviral activities are attributed to punicalagin, punicalin, ellagic acid, punicic acid and anthocyanins [6]. These data are mostly *in vitro*; confirmation in food systems and humans is still limited [4, 6].

DISCUSSION. Choice of extraction method. The evidence shows a consistent trade-off.

Conventional solvent extraction maximises total phenolics but is slow; UAE and MAE cut time and solvent use; PLE and subcritical water avoid organic solvents and allow targeting of tannins; PEF and HVED offer selectivity; and enzyme pre-treatment improves release from the fibre matrix [3, 5]. Reported values differ in cultivar, solvent, standard (GAE versus TAE) and dry-matter basis, so a single "best" method cannot be named; direct side-by-side comparison on the same raw material is needed [3, 5].

Toward complex processing. Based on the reviewed data, the following cascade (the authors' synthesis, not a single published process) can improve technology: (1) separation of peel, seeds and arils after juicing; (2) seed drying and oil recovery, with attention to the limited oxidative stability of the oil [1]; (3) peel drying, milling and, where useful, a physical or enzymatic pre-treatment; (4) green aqueous or aqueous-ethanol extraction by UAE or MAE, preferably with vacuum or temperature control to protect polyphenols [3]; (5) optional purification of punicalagin by chromatography [5]; (6) stabilisation by encapsulation or drying; and (7) use of the extracted peel residue and seed fibre as dietary fibre ingredients [1, 4]. Such a scheme reduces waste, supports a circular economy and adds value from every fraction [1].

Limitations and gaps. Most studies are laboratory-scale; industrial-type data exist for few methods. Phenolic content varies with cultivar and region [3], so raw-material standardisation is needed. Energy consumption, solvent recovery and techno-economic assessment are rarely reported. Stability of punicalagin and ellagitannins during processing and storage, and safety and efficacy in food and human studies, require further work [4, 6]. For Central Asian cultivars, systematic characterisation is still sparse [7]. This review is narrative and does not follow a systematic protocol, so selection bias is possible.

CONCLUSIONS. Pomegranate peel is the principal source of antioxidant polyphenols, with punicalagin as the dominant compound; seeds provide punicic-acid-rich oil and fibre.

Green, intensified extraction (UAE, MAE, PLE/subcritical water, PEF/HVED, enzymatic and DES-based methods) is faster and more efficient than conventional solvent extraction, but results are not yet comparable across studies. Encapsulation and food incorporation convert extracts into stable antioxidant functional ingredients. The most effective improvement is an integrated cascade processing all fractions; priorities for research are pilot-scale validation, standardised comparison on local cultivars, stability studies and techno-economic and safety assessment.

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