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Avocado seed-derived bioactive compounds for functional food packaging solutions: current developments and future prospects – a review

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A B S T R A C T

Growing environmental and food safety concerns have spurred interest in functional food packaging solutions using agricultural waste as sources of bioactive compounds that offer enhanced protection, shelf-life extension, and intelligent food monitoring. Among various agro-industrial byproducts, avocado seeds represent a promising yet underutilized resource. Avocado waste is rising with increased commercialization, utilizing the seed for value-added applications can help reduce this unrecyclable byproduct from the industry. Avocado seeds are rich bioactive compounds such as polyphenols, flavonoids, tannins and other phytochemicals. These avocado seed-derived bioactive compounds possess well documented antioxidant, antimicrobial, and pH-sensitive properties which can be harnessed to develop functional food packaging material. Moreover, use of avocado seed bioactive extracts provides a sustainable, cost-effective solution while reducing environmental impact.

While the phytochemical profile and health benefits of avocado seed extracts are well-documented, their direct integration into food packaging materials remains underexplored, underscoring a critical research gap. The objective of this review is to examine current progress in the integration of avocado seed-derived bioactive compounds into food packaging systems, with emphasis on their functional roles and impact on film performance. By revising existing studies, identifying knowledge gaps and proposing future research opportunities, this review seeks to provide insights into the feasibility and advantages of using avocado seed extract in food packaging solutions, thereby supporting the broader objectives of minimizing environmental impact and advancing sustainability in the packaging industry.

1. Introduction

Conventional food packaging mainly functions as an inert shield against external elements like moisture, oxygen, and microbial threats (Bhargava et al., 2020; Latos-Brozio & Masek, 2020; Yildiz et al., 2021). Yet, increasing awareness of environmental pollution, food degradation, and the rising demand for safer, eco-friendly food solutions has accelerated the shift toward functional packaging innovations (Boonsiriwit et al., 2021; Choi et al., 2023; Kong et al., 2023). Functional packaging offer added benefits beyond basic protection, such as extending shelf life and/or monitoring food quality through indicators like pH or temperature (Amin et al., 2022; Farhan & Hani, 2023; Zhang et al., 2022). Functional packaging contributes to improved food safety, reduced waste, and enhanced traceability in the food supply chain (Liu et al., 2022; Moreira et al., 2018). Increasingly, the packaging industry is turning to biodegradable and bio-based materials sourced from renewable resources to address the ecological footprint of petroleum-derived plastics (Ballesteros-mártinez et al., 2020; Grisales-mejía et al., 2024). One of the most promising strategies in this context is the valorization of agricultural waste, a process that involves converting agri-food byproducts into value-added components such as biopolymers, antioxidants, or antimicrobials for packaging applications (Amokrane-Aidat et al., 2024; Dobrucka et al., 2025; Lucarini et al., 2020).

Seeds derived from agricultural waste are increasingly recognized as rich sources of bioactive compounds suitable for functional food applications due to their antioxidant, antimicrobial, and nutritional properties (Amokrane-Aidat et al., 2024; Anh et al., 2024; Kuchaiyaphum et al., 2024). Fruit seeds such as those from avocado, mango, and grape have

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shown high concentrations of polyphenols, flavonoids, and dietary fiber, which contribute to food preservation and offer added health benefits (García-Mahecha et al., 2023; Ivanov & Godjevargova, 2024; Lima et al., 2021). Utilizing these seed by-products supports circular economy practices by reducing agro-industrial waste while enhancing the functional attributes of food packaging (Marotta et al., 2025; Sani et al., 2023).

Avocado fruit is widely cultivated across most tropical and subtropical regions that offer favorable environmental conditions (Angajala et al., 2019; Tesfaye et al., 2022). It is an extensively consumed fruit, due to its exceptional versatility, which encompasses its rich nutritional value, medicinal properties, and diverse applications in culinary, health, and wellness fields (Kupnik et al., 2023; Nyakang'I et al., 2023). The avocado seed, a byproduct of avocado fruit production constitutes approximately 13 %–20 % of the fruit's total weight, is often considered waste and hence discarded. According to Villarreal-Lara et al. (2019), the large volumes and low biodegradability characteristic of avocado seeds poses a serious challenge for the avocado industry (Villarreal-Lara et al., 2019). If not effectively discarded and released into the environment, avocado seeds contributes to environmental issues like greenhouse gas emission and pest problems (Ahmad & Danish, 2022; Sandoval-Contreras et al., 2023). Recent studies have demonstrated that avocado seeds are rich in bioactive compounds, including dietary fibre and polyphenols which exhibit medicinal, antioxidants and antimicrobial properties as displayed in Fig. 1 (Angajala et al., 2019; García-Vargas et al., 2021). Furthermore, avocado seed extract possesses pH-responsive properties, making them ideal candidates for use in functional packaging systems (Tesfaye et al., 2022; Üren & Kutlu, 2024). However, despite these attributes, avocado seeds are still largely under-utilized and contribute to agricultural waste within the avocado industry (Alkhalaf et al., 2019; Grisales-mejía et al., 2024). This review explores the potential of avocado seed-derived bioactive compounds in the development of functional food packaging material. The objective is to evaluate the scientific evidence supporting the use of avocado seed waste in functional packaging and to identify opportunities for further research and application.In the Introduction: Remove the phrase "see Fig. 2" so that no figure is cited there.Under the subtitle "Antioxidant activity of avocado seed extract": Insert the correct citation to Figure 2 at the appropriate point in the text as indicated.

2. An overview of recent application of seed-derived bioactives in food packaging

The integration of seed-derived bioactive compounds into biopolymer-based packaging has emerged as a promising approach to develop eco-friendly functional food packaging. These natural extracts, often rich in antioxidants, antimicrobials, and pH-sensitive compounds, offer an effective means to extend shelf life, maintain food quality, and reduce synthetic additive usage (Kuchaiyaphum et al., 2024; Sani et al., 2023). Seeds, as agricultural byproducts, present a sustainable source of bioactive compounds that can be valorized to enhance the functional performance of biopolymer films (Al-Khalili et al., 2025; Amokrane-Aidat et al., 2024; Kuchaiyaphum et al., 2024).

Several studies have demonstrated this potential as summarized in Table 1. In a study by Kuchaiyaphum et al. (2024), tamarind seed coat extract was incorporated into Carboxymethyl cellulose/poly (vinyl alcohol) polymer matrix. The resultant composite film exhibited improved mechanical and UV barrier properties. In addition, film displayed antioxidant and antimicrobial inhibition against two food-borne pathogens *E. coli* and S. *aureus* (Kuchaiyaphum et al., 2024). Acquavia et al. (2023) assimilated avocado byproducts extract including seed extract into ethyl cellulose-reinforced papers. This addition improved the hydrophobic characteristic and antioxidant activity of the paper. It was also recorded that the ethyl cellulose/avocado extract reinforced paper exhibited antimicrobial activity against *Escherichia coli* and *Bacillus cereus* (Acquavia et al., 2023). In an on-going study, addition of an avocado seed extract into PVA/starch blend resulted in a pH-responsive and antibacterial active film (unpublished data). Seeds can also be a readily available source of biopolymer base that can be used in the development of functional food packaging material (Asikkutlu & Yildirim-Yalcin, 2025; Dewi et al., 2024; Taghinia et al., 2021). In a study conducted by Taghinia et al. (2021), a packaging composite film

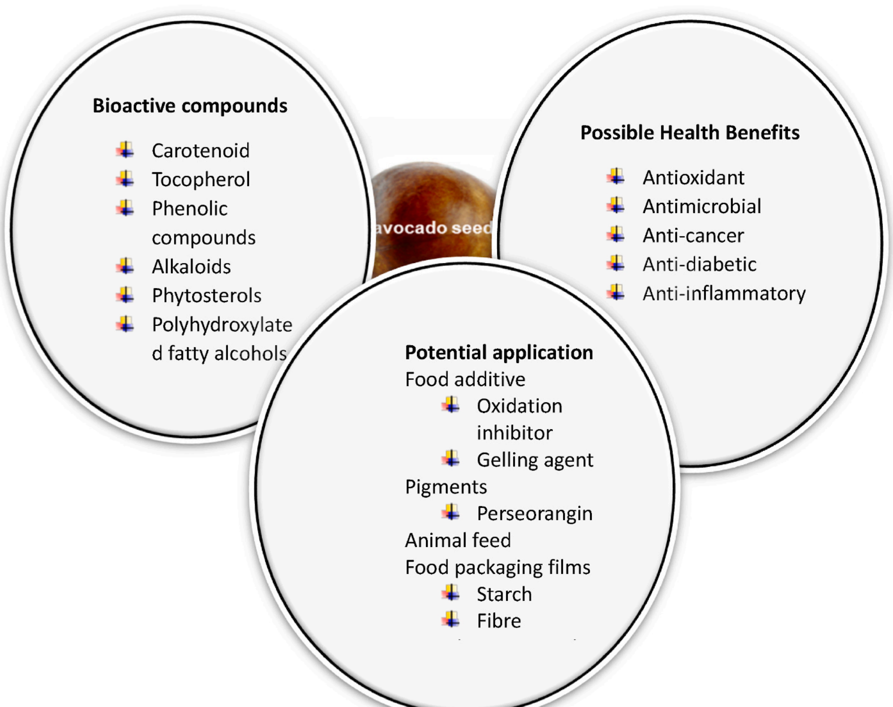


Fig. 1. A summary of the chemical composition and benefits of an avocado seed extract.

Table 1
A summary of seeds used in fabrication of functional packaging materials.

Source	Key Compounds	Functional Roles	Application in Films	References
Mekwiya date seeds	Phenolic acids and flavonoids	Antioxidant and antimicrobial	gelatin-kappa carrageenan	Amokrane-Aidat et al. (2024)
Grapefruit seed extract	flavonoids, tocopherol and other polyphenolic compounds	Antibacterial and food preservation	poly(ε-caprolactone)/chitosan films for	(Wang et al., 2019)
		Antimicrobial		(Ivanov & Godjevargova, 2024)
Mango	Gallic, caffeic, cinnamic, tannic, and chlorogenic acids	Antioxidant	Protein/gelatin	García-Mahecha et al. (2023)
	Starch nanoparticles	Antimicrobial	Starch	(Singh et al., 2024)
	Starch	Biopolymer base	Starch/poly (lactic acid) (PLA)	Lima et al. (2021)
	Carotenoids, phenolic compounds and ascorbic acid	Antioxidant		
Tamarind seed coat	Phenolics, flavonoids, vitamin C, anthocyanin and carotenoids	Antioxidant and antimicrobial ability	Carboxymethyl cellulose/poly (vinyl alcohol) based films	Kuchaiyaphum et al. (2024)
Cannabis sativa L.	Linoleic acid	Antimicrobial	apple pectin and citrus pectin	Dobrucka et al. (2025)
Date seed	Phenolic compounds.	Antibacterial	Carboxymethyl cellulose/Polyvinyl alcohol	(Lawal et al., 2024)
		Antioxidant and antimicrobial	starch/cellulose/chitin-based packaging material	(Thakwani et al., 2023)
Sunflower Seed	Biopolymeric matrix base	Structural improvement	Galactomannans and proteins	(Alves et al., 2024)
Lallemantia iberica seed gum	Mucilage	Biopolymer base	Lallemantia iberica seed gum (LISG)/ curcumin	Taghinia et al. (2021)
Fenugreek seed	Not reported	Film structural improvement	carrageenan packaging films	Farhan and Hani (2023)
Avocado seed	Not reported	Structural improvement and antibacterial	ethyl cellulose-reinforced papers	Acquavia et al. (2023)
	Not reported	pH-indicator and antimicrobial	PVA/starch film	Unpublished data

based on *Lallemantia iberica* seed gum (LISG) and curcumin with acceptable physicochemical and bioactive properties was developed. Physical interaction of the film matrix contents was confirmed by FTIR analysis (Taghinia et al., 2021). An overview of seeds that has been used in fabrication of packaging materials and their functional significance is presented in Table 1. These examples underscore the potential of seed bioactive compounds to transform conventional biopolymer films into multifunctional packaging systems aligned with sustainability and food safety goals.

3. Phytochemical composition of avocado seeds

The phytochemical constitution of avocado seeds has been extensively profiled (Do et al., 2022), Avocado seeds are repositories of bioactive phytochemicals with significant potential for food, pharmaceutical, and packaging applications (Asikkutlu & Yildirim-Yalcin, 2025; Frasson et al., 2023; Gómez et al., 2014; Miramontes-Corona et al., 2024). These seeds contain abundant polyphenols, flavonoids, tannins, saponins, acetogenins, and alkaloids (David et al., 2022; Do et al., 2022; Soledad et al., 2021; Tremocoldi et al., 2018). A summary of the chemical composition of avocado seeds is highlighted in Table 2. These bioactive compounds contribute to seed's antioxidant, antimicrobial, and functional properties (Dabas et al., 2013; Del-Castillo-Llamosas et al., 2023; Rojas-García et al., 2022; Soledad et al., 2021). Polyphenols are the dominant class and include phenolic acids such as gallic and vanillic acid, and flavonoids like catechin, epicatechin, and quercetin (Bangar et al., 2022; Figueroa et al., 2018; Onyedikachi et al., 2024; Rojas-García et al., 2022; Tremocoldi et al., 2018). These compounds typically possess multiple hydroxyl groups attached to aromatic rings, enabling them to neutralize free radicals through hydrogen or electron donation (Angajala et al., 2019; Marra et al., 2024; Rodríguez-Sánchez et al., 2019). The total phenolic content in avocado seed extracts varies with factors such as cultivar and extraction method, generally ranging from 6 to 180 mg gallic acid equivalents (GAE)/g extract (Hue et al., 2021; Kupnik et al., 2023). Extraction is commonly performed using 50 %–80 % aqueous ethanol or methanol (Araújo et al., 2020; Chen & Zhu, 2025; Munthe et al., 2023) via techniques like maceration, ultrasound-assisted extraction (UAE), microwave-assisted extraction, and Soxhlet extraction (Angajala et al., 2019; Araújo et al., 2020; Faizah et al., 2024; Kupnik et al., 2023; Munthe et al., 2023). Ethanol is widely preferred for its safety and efficiency in solubilizing phenolic compounds (Melgar et al., 2018; Yepes-Betancur et al., 2021). The diversity and concentration of these phytochemicals underscore the potential of avocado seed extracts for integration into functional food packaging systems.

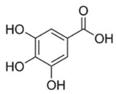
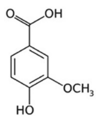
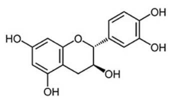
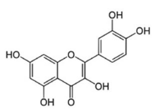
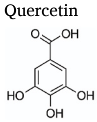
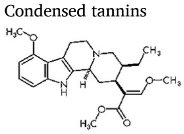
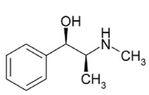
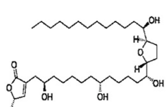
4. Bioactivity of avocado seed extract relevant to functional food application

Avocado seed extract is rich in bioactive compounds which exhibit strong antioxidant, antimicrobial, and anti-inflammatory activities properties that are valuable in functional food applications (Gavídia-valencia et al., 2024; Sánchez-Quezada et al., 2024; Tuong & Tran, 2024). In addition to these phytochemicals, the seed contains a significant amount of starch, which can serve as a natural biopolymer with potential uses in food formulation and packaging (Alemu et al., 2022; Chel-Guerrero et al., 2016; Silva et al., 2017; Zúniga et al., 2024). Together, these components contribute to improved food preservation, safety, and added nutritional or functional benefits. The multifunctionality of avocado seed constituents supports their use as natural ingredients in innovation food packaging technologies.

5. Antioxidant activity of avocado seed extract

Avocado seed has emerged as a promising source of natural antioxidant compounds, owing to its rich content of polyphenols, flavonoids, and other bioactive phytochemicals (Athaydes et al., 2022; Figueroa et al., 2018). These natural antioxidants have the potential to enhance the functionality of food packaging by extending the shelf-life of the packaged food (David et al., 2022; Merino et al., 2021; Moalla et al., 2021; Nyakang'i et al., 2023; Tesfaye et al., 2022). Antioxidants can be incorporated into the packaging materials themselves, either as active compounds that migrate into the food or as part of the matrix that is directly in contact with the food, thus helping to maintain its quality over time as Illustrated in Fig. 2 (A). The antioxidants function by inhibiting lipid and protein oxidation and spoilage, thus preserving the freshness of the packaged food, whilst reducing the need for synthetic preservatives (Cirillo et al., 2018; Melgar et al., 2018). Fig. 2(B & C) highlights the organoleptic changes observed due to lipid oxidation in food and the mechanism through which the oxidation process occurs.

Table 2
A summary of phytochemical composition of avocado seeds.

Chemical class	Example Compounds & Structures	Primary Functions	References
Phenolic acids	 Gallic acid  Vanillic acid	Antioxidant, anti-inflammatory, antimicrobial	(Araújo et al., 2020) v
Flavonoids	 Catechin  Quercetin	Strong radical scavenging, UV protection, antimicrobial	Munthe et al. (2023)
Tannins	 Condensed tannins	Astringent, antimicrobial, metal ion chelation	(Gavídia-valencia et al., 2024; Yepes-Betancur et al., 2021)
Saponins		Emulsifying, antimicrobial, cholesterol-lowering	Akalazu and Uchegbu (2020)
Alkaloids		Neuroactive, antimicrobial, toxic at high doses	(Akalazu & Uchegbu, 2020; Kupnik et al., 2023)
Acetogenins		Antimicrobial	Rodríguez-Sánchez et al. (2019)

The antioxidant ability of avocado seed-bioactive compound has been assessed by several researchers. However, data of the actual application into active packaging is limited and few applications in real food samples. In a study by Acquavia et al. (2023), avocado byproducts extract was obtained using ethyl acetate. It was characterized by considerable amount phenolic (7.5 mg GAE/g) and flavonoid (7 mg QE/g), contributing to strong radical scavenging activity. When incorporated into ethyl cellulose-coated filter paper, the extract functioned as a natural antioxidant agent, enhancing the material's ability to prevent oxidative degradation and extending the potential shelf life of packaged food products. This application exemplifies the extract's dual functionality as both a preservative and a component of sustainable, bioactive packaging solutions (Acquavia et al., 2023). Miramontes-Corona et al. (2024) determined the phenolic profile of two varieties of avocado (Criollo and Hass) using the Folin–Ciocalteu protocol. Antioxidant property of both cultivars was further ascertained using the ferric reducing antioxidant power (FRAP) protocol. Results indicated that the Hass extracts had superior phenolic content which was 287.41 ± 1.36 mg GAE/g dry extract compared to criollo with 207.01 ± 1.38 mg GAE/g dry extract. That translated to considerable antioxidant activities of both cultivars (1329.48 and 1276.18 μmol Fe^{2+}/g of dry seed for Hass and Criollo respectively. In another study, the amount of phenols and antioxidant property of avocado seeds were established and further assessed for possible application as an antioxidant in food (Gómez et al., 2014). The avocado extract and lyophilized powder were used to observe any effect in the impediment of oxidation in oil-in-water (O/W) blends and burgers made of beef meat over a period 8 days. Results indicated 30 % and 60 % oxidation inhibition in emulsions for the pure extracts and mixture of extracts with egg albumin, respectively. In the meat burger, Thiobarbituric acid reactive substances (TBARS) formation was evaded by 90 % (Gómez et al., 2014). Dabas et al. (2019) investigated the antioxidants and anticancer effects a coloured avocado seed extract. The coloured extract exhibited an oxygen radical absorption capacity of 2012 ± 300 Trolox equivalents per mg. The extract further decreased lipid hydroperoxide formation in an oil-in-water emulsion by 33 % at a concentration of 500 μg/mL. Using accelerated solvent extraction (ASE) and liquid chromatography coupled with Ultra-High-Definition Accurate-Mass Q-TOF, another study identified a total of 84 bioactive compounds in both the avocado seed kernel and seed coat (Figueroa et al., 2018). Assessment of the antioxidant capacity of the avocado seed kernel and seed coat extracts indicated these underutilized avocado byproduct can be of beneficial use in food packaging industry (Figueroa et al., 2018). Table 3 highlights work done on the antioxidant capacity of avocado seed. These studies emphasize the richness of avocado seed in several bioactive compounds that exhibit substantial antioxidant activity. Incorporation of avocado seed extract into biodegradable packaging materials can turn the packaging into an active material that actively protects the packaged food. This packaging material gradually releases antioxidants, helping to slow the oxidation of food products like oils, meat, and dairy.

6. Antimicrobial activity of avocado seed extracts

In addition to their documented antioxidant activity, avocado seed extracts also exhibit significant antimicrobial properties, largely due to their abundant phytochemical composition which enables inhibition of various pathogenic microorganisms (Akalazu & Uchegbu, 2020; Bahru et al., 2019; Figueroa et al., 2018; Miramontes-Corona et al., 2024). Avocado seeds also contain bioactive acetogenins which are derivatives from long chain fatty acids (Pacheco et al., 2017; Rodríguez-Sánchez et al., 2019; Salinas-Salazar et al., 2017; Villarreal-Lara et al., 2019). Acetogenins have also been proven to possess antimicrobial, insecticidal and antifungal capacity (David et al., 2022; Pacheco et al., 2017; Segovia et al., 2018). Table 3 shows recent documented antimicrobial activity of avocado seed extracts. Soledad et al. (2021) evaluated the antimicrobial activity of an ethanolic and acetone avocado seed extracts against *Staphylococcus aureus* and *Salmonella typhimurium*. The highest log reductions of both *Staphylococcus aureus* and *Salmonella typhimurium* recorded were 4.0 ± 0.3 and 1.8 ± 0.3 respectively (Soledad et al., 2021). A mixture of acetone and water (4:1) avocado seed extract was used to retard growth of *S. aureus* and *E. coli* (Miramontes-Corona et al., 2024). Do et al. (2022) determined the bacterial inhibitory properties of an ethanolic avocado seed extract on real food sample (*Litopenaus vannamei*) stored at 2 °C. In the study the avocado seed extract exhibited superior preservative effects when compared to sodium metabisulfite at 1.25 % (Do et al., 2022). In our ongoing research, preliminary findings have shown that avocado seed extract possesses antimicrobial properties (Table 4). The extract demonstrated inhibitory effects against *L. innocua* and *B. cereus*, aligning with observations reported by other researchers (unpublished data).

The above studies highlight that extracts from avocado seeds exhibit antimicrobial effects against some common foodborne pathogens. Even though, in majority of the studies on the antimicrobial activity of avocado seed extracts were evaluated directly on test organisms without further application, avocado seed extract holds promise as a natural antimicrobial agent in biodegradable food packaging. It offers a sustainable alternative to synthetic antimicrobial agents and could help address both food safety and environmental challenges.

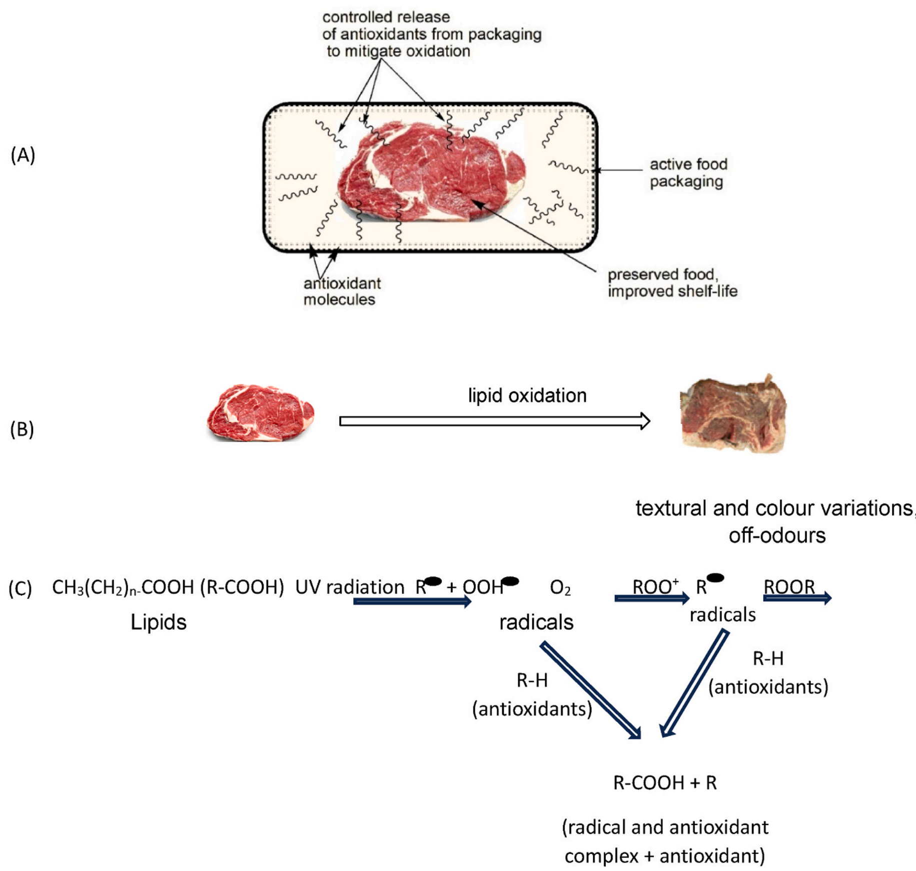


Fig. 2. Illustration of antioxidant packaging mechanism (A), illustration of visual changes of food due to oxidation (B), and illustration of lipid oxidation mechanism in food (C).

7. Avocado seed starch potential application in functional food packaging

Several studies have highlighted avocado seed as a valuable source of starch-based biopolymer, with starch content reaching up to 66.3 % on a dry weight basis (Aguilar & Tapia-Blácido, 2023; Nyakang'i et al., 2023; Tesfaye et al., 2022). Research records further indicate that avocado seed starch has following characteristics; 20 %–30 % amylose content, 70 %–80 % amylopectin (Martens et al., 2018), gelation range between 55 and 83 °C, water absorption capacity of about 22–24 g of water/g, maximum viscosity of 380–390 BU, 19 %–20 % solubility, swelling power of 28–30 g of water/g of starch (Alemu et al., 2022; Bangar et al., 2022; Zúniga et al., 2024). According to Hue et al. (2019), starch with higher amylose content has the potential to overcome some of the drawbacks associated with starch-based packaging such as poor tensile strength and its hydrophilic nature (Hu et al., 2019). A wide range of gelatinization temperature for the avocado starch has been observed (Jiménez et al., 2022) which suggests an increased degree of association amongst molecular components mainly amylose (Chel-Guerrero et al., 2016). The broad gelatinization temperature may be advantageous in biodegradable packaging development because it may improve compatibility with additives such as plasticizers and active agents. It may also allow fine-tuning of starch composites formulations and supports incorporation of multiple functional layers within a single product. These properties make starch from avocado seeds an ideal ingredient in biodegradable food packaging material (Jiménez et al., 2022).

Starch-based bioplastics typically exhibit limited mechanical strength compared to conventional petroleum-based plastics (Alemu et al., 2022; Alemu et al., 2022). Nevertheless, starch extracted from avocado seeds has been effectively used in the fabrication of biodegradable food packaging materials, either as a sole biopolymer matrix or incorporated into composite systems. Ginting et al. (2018) determined the effects of ethylene glycol plasticizer concentration on avocado starch/chitosan composite bioplastic characteristics. An acceptable bioplastic features of the avocado starch/chitosan composite were attained with the following attributes; modulus of elasticity 2031.326 MPa, density 203 g/cm^3, elongation at break 5.370 %, tensile strength 30.213 MPa, bioplastic gelatinization temperature of 91.55 °C (Ginting et al., 2018). Ginting et al. (2018) study highlights applicability of starch from avocado seeds as a source of biopolymer in manufacturing food packaging material. Jiménez et al. (2022) evaluated the potential of starch from avocado seeds by developing bioplastics using starch extracted from Hass avocado seeds. Starch was extracted via the wet milling method and the yield was recorded to be 11.38 % dry starch, which was comparable to other reported yields of 11.53 % (Vega-Castro et al., 2022) and 13.1 % (Muñoz-gimena et al., 2024), however, notably lower than other recorded yield of up to 31.24 % (Sharma et al., 2023). The starch gelatinization temperature ranged between 55 and 80 °C. The starch was then used to manufacture two types of biofilms, one without a plasticizer and the other with glycerol (plasticizer). Even though the films produced exhibited varying physicochemical properties, the study concluded that Hass avocado seed can be used as starch source for biodegradable films (Jiménez et al., 2022). In another study, starch from avocado seeds was extracted and blended with Polylactic Acid (PLA). The starch/PLA blend was further applied for the development of biodegradable plastic using the Response Surface Methodology (RSM). The film demonstrated effective biodegradability and potential for replacing conventional plastic packaging (Dewi et al., 2024). Alemu et al. (2022) also extracted starch from avocado seeds (18.3 ± 0.02 % yield) with amylose content of 17 ± 0.03 %. A bioplastic film reinforced with glycerol and cellulose from enset plant was then manufactured (Alemu et al., 2022). A recent study by Asikkutlu and Yildirim-Yalcin

Table 3
Functional properties of avocado seed extracts Relevant to food packaging.

Avocado Variety	Extraction solvent	Compound class	Metabolites quantity	Bioactivity	Method applied	Application	Key findings	References
NR	Ethyl acetate	Total phenolic compounds (TPC) (GAE/g) Total Flavonoids compounds (TFC) (QE/g)	7.5 mg GAE/g dried extract 7 mg QE/g	Antioxidant Antimicrobial	DPPH Assay The minimum inhibitory concentration (MIC)	Active food packaging	Improved antioxidant capacity and moisture barrier properties. Packaging inhibited growth of *B. cereus*	Acquavia et al. (2023)
Hass	Ethanolic aqueous	TPC (mg GAE/100g) Aqueous extract of fresh seed (RS-H_2O) Ethanolic extract of fresh seed (FS-EtOH) Aqueous extract of dry seed (DS-H_2O) Ethanolic extract of dry seed (DS-EtOH)	828.37 ± 102.9 1064 ± 32.33 433.56 ± 21.64 177.49 ± 23.89.	Antioxidant activity Antimicrobial	DPPH, ABTS and FRAP Disk diffusion	*In Vitro* antioxidant and antimicrobial activity.	FS-EtOH extract exhibited the strongest antioxidant and antimicrobial activity against *Salmonella Typhimurium* and *Listeria monocytogenes*	David et al. (2022)
Hass Criollo	Maceration -acetone/water mixture (80:20)	TPC (mg GAE/g of dry extract)	Hass – 287.41 ± 1.36 Criollo – 207 ± 1.38	Antioxidant capacity Antimicrobial capacity	Ferric reducing antioxidant power (FRAP) Disk diffusion method	*In Vitro* antioxidant and antimicrobial activity.	Avocado seed extract exhibited antibacterial activity against *Staphylococcus aureus* ATCC 6538 and *Escherichia coli* ATCC 8739 strains.	Miramontes-Corona et al. (2024)
Hass	Maceration - ethanol-water mixture 80/20 (v/v)	TPC (mg/g DE)	14 ± 1	Antioxidant activity	TEAC, FRAP and ORAC	*In Vitro* Antioxidant activity.	Avocado seed extract antioxidant capacity inferior compared to leaf extract in this study.	Rojas-García et al. (2022)
NR	chloroform/methanol extraction	Total sterols	3.21 %	Antioxidant effect	DPPH and ABTS	*In Vitro* Antioxidant.	Results indicated significant ATBS and DPPH inhibitory capacity	Alkhalaf et al. (2019)
Hass	Soxhlet extraction	TPC (GAE/100 g) Aqueous extract (AE) Ethanolic extract (EE) TFC AE EE	0.31 ± 0.06 0.18 ± 0.03 0.45 ± 0.13 0.67 ± 0.02	Antioxidant activity	TEAC and FRAP	*In vitro* antioxidant capacity.	Avocado seed extract exhibited antioxidant capability; however lesser efficiency compared to leaf extract in this study.	García-Vargas et al. (2021)
Criollo	Ethanol and acetone	TPC (mg GAE/100 g) Ethanolic extract Acetone extract	0.25 ± 0.21 30.80 ± 0.84	Antioxidant activity Antimicrobial capacity	DPPH Log reduction	*In vitro* antioxidant and antimicrobial capacity.	Acetone extracts presented superior capability than ethanol extract. Antimicrobial activity was observed against *S. aureus* and *S. Typhimurium*	Soledad et al. (2021)
Hass	Turbolysis (10 % w/v) with 70 % ethylic alcohol (SCE), Hexanic (SHP) and Ethyl acetate (SEAP)	TPC – SCE SEAP SHP TFC – SCE SEAP SHP Tannins – SCE SEAP SHP	58.75 ± 0.76 366.79 ± 5.05 13.69 ± 0.50 14.76 ± 0.35 28.09 ± 0.64 12.86 ± 0.51 36.13 ± 1.60 314.64 ± 253 3.27 ± 4.12	Antioxidant Activity Antimicrobial activity	DPPH AND ABTS Minimal Inhibitory Concentration (MIC)	*In vitro* antioxidant and antimicrobial capacity.	SEAP presented higher antioxidant activity. The growth *H. pylori* was inhibited by the hexanic and ethyl acetate avocado seed extract	Athaydes et al. (2022)

(*continued on next page*)

Table 3 (*continued*)

Avocado Variety	Extraction solvent	Compound class	Metabolites quantity	Bioactivity	Method applied	Application	Key findings	References
Fuerte	Ethanolic extract	NR	NR	Antimicrobial activity	Agar well diffusion	*In vitro* antibacterial activity	Ethanolic extract inhibited *Listeria innocua* (ATCC 33090) *Bacillus cereus* (ATCC 10876)	Unpublished work

NR = Not reported.

Table 4
An overview of biodegradable packaging manufactured from avocado seed starch.

avocado cultivar	Extraction method	Anti-browning agent	Yield and Physicochemical properties	Application	References
NR	Wet milling	0.2 % wt Sodium hydroxide (NaOH)	Yield 20.31 % (on wet basis), Smooth, orange-white powder, Humidity –13.045 %, Protein - 3.449 %, Lipids - 1.501 %, Ash - 0.283 %, Carbohydrates - 81.721 %, Amylose - 29.651 %	PLA/modified starch bio-composite film for UV-blocking	(Godoy et al., 2024)
NR	Physical extraction	NR	Yield 18.3 %, Moisture 12.7 %, Ash 0.67 %, pH 5.73 %, amylose 17 %, Amylopectin 83.2 %, Swelling power 7 g water/g of starch, Solubility 20.6 %, high crystallinity	Starch/Enset Cellulosic blend film	Alemu et al. (2022)
NR	Wet milling	0.2 % (w/v) sodium metabisulfite	amylose - 29.7 %.	Starch/Ginger essential oil (GEO) for antibacterial activity against *Escherichia coli* (ATCC 43895).	(Pires et al., 2024)
NR	Physical extraction	NR	NR	Avocado seed starch/PLA composite film	Dewi et al. (2024)
Hass	Wet milling	Sodium bisulphite (1/5 m/v) ratio	Starch yield 11.53 %, Starch purity 41.8 g/100 g Gelatinization – maximum viscosity 950 *BU* at 93.2 °C and 950 *BU* after cooling,	Edible Starch coating for potatoes French fries	Vega-Castro et al. (2022)
NR	Wet milling	200 ppm sodium metabisulfite	NR	Nano chitosan/starch edible film to monitor shelf life of strawberry fruits	(Suhartini et al., 2023)
NR	Wet milling	sodium metabisulfite solution 0.2 % (v/v)	Yield - 31.24 %, Starch purity - 82.56 %, Colour – white, Texture – velvety, Moisture – 9.87 %, Fat – 4.72 %, Proteins – 3.65 %, Ash – 0.04 %, Crude fibre – 0.18 %, maximal viscosity - 706 *BU* at 88.1 °C	Starch/cellulose composite films	Sharma et al. (2023)
Hass	Physical extraction	NR	Yield - 11.38 %, Moisture – 12 %, Ash – 0.16 % Gelatinization; minimum temp 55 °C maximum temperature 80 °C	Starch biofilm preparation	Jiménez et al. (2022)
Hass	Wet milling	Sodium bisulphite solution 1:5 (v/w)	Yield - 13.1 % Colour – light brown	Avocado Seed Starch/starch nanocrystal film	Muñoz-gimena et al. (2024)

NR = Not reported.

(2025) demonstrated that avocado starch biopolymer can be used as a base matrix for functional ingredients. In this study an extract form blue butterfly pea flower was incorporated in an avocado seed starch extract and the composite was subsequently used as a chicken breast meat spoilage indicator. The variation in pH and bacterial count was monitored over 3 days storage time. It was observed that as the meat quality depreciated, the microbial growth and pH increased, the composite film colour transitioned from blue to green. The results from the study highlights the potential of avocado seed-derived starch in active packaging. Table 4 presents an overview of biodegradable packaging material that has been developed using starch from avocado seeds.

8. Broader functional applications of avocado seed extracts

Microencapsulated avocado seed extract can be added to food packaging as a functional additive. Kautsar et al. (2023) encapsulated an avocado seed extract in Gum Arabic through dry spraying method. The microencapsulated avocado extract was further evaluated for its antimicrobial and antioxidant activity. Gram-positive *S. aureus* and Gram-negative *E. coli* was used as test organisms and the results indicated that the encapsulated extract inhibited growth of both test organisms up to 6 days. The antioxidant activity of the encapsulated extract decreased from 94.82 % to 92.46 % on the seventh day (Kautsar et al., 2023). In another study an extract from avocado seeds was successfully encapsulated into zein nanoparticles (Chuacharoen et al., 2024). These studies showcase the potential application of microencapsulated avocado seed extract as an active ingredient in food packaging material. The microencapsulated avocado extract can be released over an elongated period of time thus improving the shelf-life of the packaged food. Another application of an avocado seed extract has been its use as an alternative source of natural food dye since a water extract of an avocado seed displays an orange colour (Bangar et al., 2022; Hatzakis et al., 2019; Sánchez-Quezada et al., 2023). This colour property of an avocado seed extract can be beneficial if incorporated into food packaging that require protection from light (Ndwandwe et al., 2022).

Extracts from avocado seed have been proven to have health-promoting properties such antidiabetic, anticancer, anti-obesity, anti-inflammation, antioxidant and even antimicrobial capacity (Bangar et al., 2022; Dabas et al., 2019; Sánchez-Quezada et al., 2023). They are abundant in nutrients, including carbohydrates, proteins, bioactive compounds and minerals (Nyakang'I et al., 2023). Avocado seeds can be processed into an edible packaging that can be consumed along with food with an added advantage of the health-promoting properties. This will not only reduce waste but also add novelty to the packaging material. In one study an edible coating was prepared to decrease the oil uptake and acrylamide quantity in French fries. It was concluded that avocado seed starch has the potential as cost-effective and practical alternative as an effective coating to minimize the acrylamide quantity in French fries (Vega-Castro et al., 2022). Among the macro nutrients found in an avocado seed is fibre hence an alternative source (Barbosa-Martín et al., 2016). This fibrous structure of avocado seeds can be used to reinforce food packaging. Incorporating powdered avocado seeds into food packaging can possibly enhance its strength and durability while maintaining a sustainable profile. Amelia et al. (2024) chemically treated avocado seed waste and further used it as a cellulose-rich filler in the synthesis of gelatin-based film with improved mechanical strength. The created composite material can be applied in different kinds of food packaging offering a balance of strength, non-toxicity and flexibility. Avocado seed extract can also be used in green nanotechnology for synthesis of non-toxic nanoparticles which can further be used in the development of bioplastics (Saridewi et al., 2022). The various applications highlight the potential of avocado seeds to contribute to more practical and functional food packaging. This aligns with growing trends towards waste reduction and environmental responsibility.

9. Benefits of using avocado seed in food packaging

The application of avocado seed extracts in food packaging material manufacturing is an innovative strategy that combines sustainability and practicality. Benefits associated with such innovation may include waste reduction. Avocado seeds are often regarded as waste (Ahmad & Danish, 2022; Kautsar et al., 2023) hence repurposing them for packaging can contribute to minimizing food waste. Also, the biodegradability of avocado seed extracts is an advantage, therefore, packaging material from avocado seed can have reduced environmental impact as compared to traditional plastics. Avocado seeds are a renewable resource. The avocado industry is growing and so is waste generation during avocado processing. This makes avocado seeds readily available resource in large quantities. One cannot overlook the most researched aspect of avocado seeds and i.e. their natural biological activities. Avocado seeds have a natural antimicrobial and antioxidant properties. Both properties can be beneficial in prolonging the freshness of food if incorporated in food packaging material. The considerable nutritional value of avocado seeds also presents an added advantage to food packaging more especially edible food packaging. Lastly, using avocado seeds in developing packaging material may represent a cutting-edge approach to material science and sustainability with a potential in leading to new products and advancements.

10. Possible challenges of avocado seed-based food packaging and potential solutions

While avocado seed extracts show promise for use in functional food packaging, several challenges must be addressed to ensure their viability in commercial applications. One major challenge involves the efficient extraction and processing of bioactive compounds from avocado seeds. These processes can be technically demanding and resource-intensive. However, advances in green extraction technologies such as ultrasonic-assisted extraction, enzymatic treatment, and optimized drying and milling processes can offer more cost-effective and environmentally friendly alternatives to improve yield and consistency. Another limitation is the performance of avocado seed-based packaging materials, particularly in terms of mechanical properties such as durability, tensile strength, and flexibility. These properties often fall short when compared to conventional petroleum-based plastics, potentially affecting the material's reliability and suitability for various food packaging applications. Furthermore, achieving adequate barrier properties such as resistance to oxygen, moisture and other undesired contaminants is critical for maintaining food quality and shelf life, yet can be challenging with starch-based bioplastics. However, there are several mitigation strategies that can be employed. These include incorporation of reinforcing agents such as natural fibres, nanoclays, or cellulose nanocrystals. Also, blending starch with compatible biopolymers like polyvinyl alcohol (PVA) or polylactic acid (PLA) can improve both mechanical and barrier properties. Additionally, crosslinking agents (e.g., citric acid or glycerol) can modify the polymer network, reducing water solubility and improving structural integrity. These strategies, in combination or individually, can help improve the functional performance of avocado seed-based films to meet the demands of food packaging applications.

Economic viability also presents a critical challenge in the production of avocado seed-based packaging materials. The cost of production may be higher than that of conventional petroleum-based plastics, potentially impacting market competitiveness. Additionally, scaling up from small-scale or laboratory production to industrial levels involves significant financial investment, technical expertise, and infrastructure, making the process both complex and expensive. However, the use of avocado seeds as an agro-industrial waste resource can contribute to cost reduction of raw materials while promoting waste valorization. Further cost reductions can be achieved through process optimization and the adoption of energy-efficient, green technologies. Strategic integration with existing food processing and packaging facilities can also minimize capital costs by leveraging shared infrastructure. Moreover, support through public-private partnerships, government incentives, and sustainability-driven funding can provide the necessary financial and technical backing to improve scalability and competitiveness in the market.

Consumer acceptance of packaging materials derived from avocado seeds may also present a challenge, particularly due to concerns about the safety, efficacy, and unfamiliar origin of the product. Since the material is made from an unconventional and previously discarded source, some consumers may be hesitant to trust its suitability for food contact applications. To address this, transparent communication and education are essential. Providing clear labelling that highlights the biodegradable, food-safe, and eco-friendly nature of the packaging can build consumer trust. Additionally, obtaining and displaying compliance with recognized food safety standards and certifications can help assure consumers of the material's safety. Conducting awareness campaigns, engaging in sustainability-focused branding, and offering evidence of performance and environmental benefits can further enhance acceptance and market uptake. Another challenge in using avocado seed-based materials is ensuring a consistent and reliable supply of raw material to support large-scale production. While it may appear that availability could be limited by seasonality, this is effectively mitigated by the fact that avocado production is continuous throughout the year due to global cultivation in diverse regions such as Mexico, Peru, and Spain. This widespread and year-round availability of avocado seeds as an agro-industrial byproduct ensures a steady supply chain, making it feasible to maintain consistent formulation and scale-up manufacturing for commercial applications. Establishing sourcing partnerships with avocado processing industries in these regions can further enhance supply reliability and reduce procurement risks.

11. Gaps identified

While the bioactive properties of avocado seed extracts have been widely investigated, especially their antioxidant and antimicrobial activities, there remains a significant gap in the translation of this knowledge into practical packaging applications. Most research has focused on the characterization of bioactive compounds, with only minimal content dedicated to their incorporation into biodegradable packaging materials and subsequent food application trials. This underrepresentation signals a broader research gap in the field. Furthermore, there is limited information on the integration of avocado seed extracts into film matrices, their functional impact on packaging material properties, or their effectiveness in preserving diverse real food products. The scarcity of such applied data restricts the understanding of the practical viability, scalability, and regulatory implications of using avocado seed-derived compounds in food-grade packaging. This gap underscores the need for studies that go beyond *in vitro* evaluations and explore real-world applications, shelf-life extension trials, and consumer safety considerations. Additionally, one of the most intriguing yet underexplored characteristics of avocado seed extract is its colour development in the presence of air (Dabas et al., 2011). This oxidative browning behaviour has not been fully explored in packaging applications, where it could be leveraged as a **natural indicator of food quality or environmental conditions.** Considering that packaging materials are often in direct contact with the atmosphere, to ensure functionality and prevent premature oxidation, the indicator component derived from avocado seed extract can be strategically incorporated into the inner layer of the packaging material, rather than being exposed to ambient atmospheric air. The use of Modified Atmosphere Packaging (MAP) can further support this design by creating a controlled internal environment. This approach allows the indicator to respond selectively to changes within the package headspace such as oxygen ingress or spoilage, thereby enhancing its value as a visual sensor for freshness and product integrity. This feature could provide supplementary layers of functionality beyond mere aesthetics. Exploring and leveraging the colour properties of avocado seed extract opens innovative avenues for packaging design. This can lead to unique, custom solutions that can be outstanding in the market.

12. Future directions and conclusion

The future for the application of avocado seed in the manufacture of packaging lies in research and development. Further investigation on the characteristics of avocado seed materials and their optimization for packaging usage is still essential. Developing cost-friendly and efficient protocols for processing avocado seeds into packaging material will be critical. Exploring the potential of blending avocado seed material with other biodegradable or renewable materials could possibly improve its applicability and performance. Regulatory and safety assessment of avocado seed materials should also be considered as this will ensure that avocado seed-based packaging adhere to food safety standards and regulations for extensive adoption. Implementing pilot projects and collaborations with the food industry to evaluate and refine packaging material based on avocado seeds could help to demonstrate its benefits and viability. Also, consumer education on the environmental benefits and safety associated with the usage of avocado seeds in packaging could foster acceptance and improve demand. Lastly, avocado seeds represent a promising and underutilized resource for the food packaging sector. The multifunctional potential of avocado seed extracts in food packaging is compelling particularly when considering the limited research conducted in its colour variation. As research and technology advances, there is an opportunity to fully realize the benefits of this material. By emphasizing on its sustainability and unique aesthetic characteristics, avocado seed-based packaging could become a significant player in the future of environmentally conscious and functional packaging solutions. The use and benefits of avocado seed extracts extends well beyond its current application.

CRediT authorship contribution statement

Bongekile K. Ndwandwe: Writing – original draft, Methodology, Investigation, Conceptualization. **Soraya P. Malinga:** Writing – review & editing, Supervision, Funding acquisition. **Eugenie Kayitesi:** Writing – review & editing, Supervision. **Bhekisisa C. Dlamini:** Writing – review & editing, Methodology, Conceptualization.

Ethical guidelines

No ethics approval was required for this research.

Declaration of competing interest

The authors have no conflict of interest to declare.

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Data availability

No data was used for the research described in the article.

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