



REVIEW ARTICLE

Rambutan seeds and peels as sustainable alternatives for functional foods and cocoa butter

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Abstract

Rambutan (*Nephelium lappaceum* L.), a tropical fruit native to Southeast Asia, presents significant potential across nutritional, medicinal and industrial domains. This review consolidates current research on the valorisation of Rambutan by-products, particularly seeds and peels- highlighting their rich bioactive compound composition, including flavonoids, tannins, geraniin and epigallocatechin gallate, a potent anti-cancerous compound. These constituents exhibit potent antioxidant, antidiabetic, antihypercholesterolemic and antimicrobial activities. Physicochemical analyses of rambutan seed oil from varieties R4, R7 and Serjan reveal favourable thermal and compositional profiles, including high levels of arachidic and oleic acids, positioning it as a viable alternative to cocoa butter. Processing techniques such as fermentation and roasting enhance the oil's sensory and nutritional attributes, while toxicity assessments confirm its safety for consumption. Despite promising findings, gaps remain in mechanistic understanding, clinical validation and industrial scalability. Future research should focus on molecular pharmacology, compound isolation and integration into circular-economy models to fully harness the potential of Rambutan by-products for sustainable food systems and functional applications.

Keywords: antidiabetic; agricultural waste; antimicrobial activities; antioxidant; antihypercholesterolemic; bioactive compounds; physicochemical properties; Rambutan seed oil; valorisation

Introduction

The growing global emphasis on sustainable food systems has increased the need for alternative sources of functional ingredients and fats that enhance nutrition and industry while minimizing agricultural waste. Rambutan (*Nephelium lappaceum* L.), although primarily appreciated for its sweet edible flesh, produces significant by-products such as seeds and peels that are often discarded. These by-products contain a wealth of bioactive compounds, including flavonoids, tannins and distinctive fatty acid profiles, which have promising potential for nutraceutical, medicinal and industrial uses. rambutan is a tropical fruit belonging to the Sapindaceae family. It originates from Malaysia and its name is derived from the Malay word "Rambut," which means "hair," referring to the fruit's soft spines. The fruit is edible, typically ranging in colour from red to orange, with a leathery skin covered in flexible, spiny hairs. Its shape varies from oval to spherical (1). Major producers and exporters of rambutan include Indonesia, Malaysia and Thailand (2). Rambutan production is largely concentrated in Southeast Asia, where tropical climatic conditions favour large-scale cultivation. Thailand is currently the leading producer, with an estimated annual production of approximately 450,000 tonnes, followed by Indonesia

with about 100,000 tonnes and Malaysia with nearly 60,000 tonnes. Collectively, Southeast Asian countries account for more than 75 % of global rambutan output, underscoring the region's dominance in cultivation and export markets. Global production has been estimated at around 3.4 million metric tonnes, driven by increasing demand for exotic fruits and value-added processing industries (3).

Thailand alone accounts for a substantial share of global supply and remains the largest exporter of fresh rambutans worldwide (4).

Rambutan area and production in India

In India, rambutan cultivation is still in its early stages and is primarily confined to humid tropical regions such as Kerala, Karnataka, Tamil Nadu and parts of the North-Eastern states. The estimated area under rambutan cultivation remains relatively small, less than 1000 acres and commercial orchards are still developing compared with Southeast Asian production systems. The fruit was introduced to India approximately seven decades ago, initially grown in home gardens before gradually expanding into commercial plantations under exotic fruit diversification programmes (5). Recent regional assessments indicate increasing commercial adoption, particularly in Kerala, where Rambutan production reached approximately

22,500 tonnes, reflecting a growing shift towards high-value exotic fruit cultivation (6).

This review emphasises the often-overlooked value of rambutan by-products-particularly the seeds and peels -which are rich in bioactive compounds such as flavonoids, tannins, geraniin and epigallocatechin gallate. These compounds exhibit potent antidiabetic, antihypercholesterolemic, antioxidant and antimicrobial properties, as supported by *in vivo* studies demonstrating dose-dependent reductions in blood glucose and cholesterol levels. The physicochemical properties of rambutan seed oil, including its high levels of arachidic and oleic acid, semi-solid state at room temperature and favourable melting and crystallisation profiles, make it a promising alternative to cocoa butter. Additionally, fermentation and roasting processes enhance its sensory and nutritional qualities, encouraging its use in functional foods and nutraceuticals.

The purpose of this review is to consolidate diverse research on rambutan seeds and peels, thereby providing a comprehensive understanding of their nutritional, functional and technological properties. Connecting emerging research with practical uses of rambutan by-products such as testa, embryo, shell residues and processing waste fractions have now been included to broaden the scope of by-product valorization. in food technology and related sectors which provides researchers with a consolidated evidence base to direct future investigations, while offering industry stakeholders insights into the sustainable applications of rambutan seed fat and peel extracts for enhanced products. Nutritionists and health professionals can also gain from learning about the therapeutic potential of rambutan in addressing chronic illnesses. Overall, the main aim of the present review is to provide both scientific insights and practical viewpoints on converting underutilized fruit by-products into valuable resources that promote health, sustainability and economic development.

Botanical description

The rambutan is a moderately large, evergreen tree reaching a height of 12-20 meters, characterized by light- to dark-green compound leaves. These leaves measure 10-30 cm in length and 5-15 cm in width. The fruit itself measures 3-6 cm in length and 3-4 cm in width, with a seed approximately 2-3 cm long and very dark brown in color (7). In terms of dry weight distribution, the total weight of the rambutan fruit comprises 26.4 %, while peel comprises 14.2 %, pulp 12.1 %, seed 2.59 % and embryo 1.56 %. The fruit flesh is juicy, white and transparent or light pink, with a thickness of 0.4-0.8 cm, offering a slightly sour or sweet taste. The seed is covered by the pulp and is ovoid or oblong, measuring around 2.5-3.4 × 1-1.5 cm (8). Rambutan can be consumed fresh, used in pies, stuffed with pineapple, or processed into canned syrup (9). A variety of products, including juice, marmalade, syrup and preserves, can be made from rambutan (8). The fruit also possesses medicinal properties that can help relieve symptoms of fever, diarrhoea and digestive issues.

Rambutan has attracted significant scientific and industrial interest due to the multifunctional applications of its edible portions and its processing by-products. Beyond fresh consumption, rambutan pulp is widely utilized in the preparation of juices, canned products, syrups, marmalades, fermented beverages and dessert formulations owing to its pleasant flavor and high moisture content (2). In recent years, greater attention has been directed toward the valorization of rambutan seeds and peels, which are rich in bioactive

compounds and functional lipids. Rambutan seed fat, characterized by a high proportion of long-chain saturated fatty acids such as arachidic acid, has been investigated as a potential cocoa butter alternative or improver in confectionery and bakery applications due to its comparable melting behavior and solid fat profile (10, 11).

The seeds can also be processed into flour or roasted powder, which has demonstrated potential as a cocoa-like ingredient in bakery products and chocolate analogues after fermentation and roasting treatments that enhance flavor and the development of volatile compounds (12, 13). Rambutan peel extracts have been extensively studied for their high levels of phenolics and flavonoids, including geraniin and ellagic acid, which exhibit strong antioxidant and antimicrobial activities, making them suitable for functional food formulations and natural preservative systems (14, 15). Additionally, Rambutan by-products have shown promise in nutraceutical applications, active food packaging and dietary fiber enrichment, thereby contributing to sustainable agro-industrial waste management and circular economy strategies (2). Collectively, these diverse applications highlight the technological and nutritional importance of Rambutan and its by-products, supporting their integration into functional food development, specialty fats and value-added agricultural innovations.

Uses and applications of Rambutan

Fruit seeds and rinds, often discarded as waste, have not been extensively studied for their potential reuse or recycling. Notably, these parts of certain fruits can contain higher concentrations of vitamins, fibres, minerals and other essential nutrients compared to the pulp (16). Rambutan seeds contain 12.4 % crude protein, 38.9 % crude fat, 48.1 % carbohydrates (by difference), 3.31 % moisture and 2.26 % ash (17). These seeds are known for their bitterness and are recognized to have narcotic effects due to the presence of alkaloids. The testa of the seeds contains saponins and tannins. Although raw Rambutan seeds are considered poisonous, they are roasted and consumed in the Philippines (8).

Effect of storage conditions on seed germination of rambutan

Storage duration and conditions significantly affected rambutan seed emergence. Nearly 100 % of Rambutan seedlings emerged immediately after extraction when seeds were sown fresh, but the germination dropped to around 40 % after seven days of room-temperature storage, aligning with findings of a separate investigation, which showed a 50-65 % emergence range after similar storage periods (8). Conversely, seeds stored in a cold chamber exhibited minimal emergence after seven days. Notably, dry-chamber storage conditions maintained the highest seedling emergence rates, suggesting their effectiveness in preserving seed vigour for at least 7 days. This is corroborated by observations of reduced seed moisture correlating with diminished seedling emergence over time, with room storage showing a significant decrease in seed moisture from 34.77 % to 18.81 % within seven days ($r = 0.96$, $p < 0.01$), consistent with previous studies. Furthermore, the selection of an appropriate growing medium plays a crucial role in influencing both the germination of rambutan seeds and the subsequent growth and development of seedlings. (8, 18, 19).

Moreover, seedling growth parameters, such as leaf development and root length, were influenced by storage conditions. Despite higher seedling emergence in dry chambers, seeds stored at room temperature for seven days produced

seedlings with longer roots, indicating a complex relationship between storage conditions and subsequent seedling growth. Similar observations were reported in another study, which noted that optimal conditions for seedling emergence might differ from those for seedling growth (17). External environmental factors, viz., light and temperature and internal factors, viz., endogenous phytohormones, viz., gibberellic acid and abscisic acid, significantly affect plant growth after germination. These findings underscore the importance of maintaining appropriate seed moisture levels and selecting optimal storage conditions for successful rambutan seed germination and seedling development, providing a foundation for future research to further enhance understanding and management of rambutan seeds (20).

Rambutan seed oil as an alternative to cocoa butter

Additionally, rambutan seeds have a high fat content, with oleic acid (42.0 %) and arachidic acid (34.3 %) as the primary fatty acids (10). The presence of arachidic acid, a C20 saturated fatty acid, is uncommon in plant seeds, as most plant seeds contain very low levels of this fatty acid. Plant seed oils generally consist mainly of unsaturated fatty acids, particularly oleic acid, while saturated fatty acids such as palmitic and stearic acids are present in relatively smaller amounts. (21, 22). Due to its high arachidic acid content, rambutan seed fat remains semi-solid at room temperature (10). This fat is edible and has been studied for its potential use in manufacturing candles, soaps and fuels (8). Some researchers propose that rambutan seed fat could be utilized as a high-premium specialty fat (10). Blending this fat with softer oils or harder fats could expand its applications. Several studies have highlighted similarities between rambutan seed fat and cocoa butter in terms of fatty acid composition, crystallization behaviour and thermal characteristics, which are critical determinants of chocolate texture and stability. Rambutan seed fat contains significant proportions of long-chain saturated fatty acids, particularly arachidic acid, contributing to a semi-solid structure and melting profile suitable for confectionery applications (11, 23). Differential scanning calorimetry and rheological evaluations have demonstrated comparable crystal formation patterns and hardness indices between rambutan seed fat and cocoa butter blends, supporting its functionality as a cocoa butter replacer or improver in chocolate formulations (23). Furthermore, studies investigating flavour development and fat blending ratios have reported that incorporation of rambutan seed fat into chocolate systems can enhance aroma, oxidative stability and structural integrity, indicating strong compatibility with cocoa butter matrices (24).

Recent compositional and foodomics analyses have also emphasized the high oleic and arachidic acid content of rambutan seed oil, which enhances oxidative stability and supports its classification as a promising sustainable lipid source for specialty fats and cocoa butter alternatives (25). Compared with conventional cocoa butter, rambutan seed fat offers additional advantages, including utilization of agro-industrial waste streams, improved resource efficiency and reduced dependence on cocoa cultivation, thereby aligning with circular bioeconomy and sustainable food processing strategies (2). Various studies have indicated that the physicochemical properties of fat from both non-fermented (10, 11, 13, 25) and fermented rambutan seeds (12, 26-29) make it a viable alternative to cocoa butter. Consequently, fermenting the entire rambutan fruit to obtain seed fat, which is like cocoa butter, is feasible since fermentation positively affects the physicochemical

properties of food products (13).

Influence of processing parameters on quality attributes of Rambutan

Processing parameters, particularly roasting time and temperature, significantly affect the quality attributes of rambutan seed powder. Studies have shown that these factors markedly affect the colour and total phenolic content of the roasted seeds ($p < 0.05$). When rambutan seeds are roasted optimally, they develop a colour profile comparable to that of cocoa powder, indicating their potential as a natural cocoa substitute in food formulations. The roasting of rambutan seeds markedly impacts the volatile compound composition, with seventeen distinct compounds identified in roasted samples. Predominant volatile compounds, including 3-methylbutanoic acid, furfural, 5-methyl-2-furancarboxaldehyde, trimethylpyrazine and tetramethylpyrazine, are known to contribute to the flavour and aroma attributes. These volatiles impart sensory qualities like those of traditional cocoa powder (15).

Furthermore, the brine shrimp lethality assay for toxicity assessments indicated that roasted rambutan seed powder is non-toxic, suggesting its safety for consumption (26). This finding is particularly important because it demonstrates the feasibility of using rambutan seeds as a sustainable, nutritious alternative to cocoa. The transformation of rambutan seeds into a cocoa-like powder involves fermentation, drying and roasting processes, effectively reducing agricultural waste while creating value-added products. This not only offers a novel use for rambutan seeds but also contributes to sustainable food production by minimizing waste and efficiently utilizing by-products (27).

Rambutan seeds are safe for consumption, as they are non-toxic and provide essential nutrients such as carbohydrates, fats and protein. Rambutan seeds have garnered scientific interest due to their bioactive compounds, including antioxidants, phenolic compounds and dietary fiber (15). They exhibit antimicrobial activity against both Gram-positive and Gram-negative bacteria, a characteristic attributed to their antioxidant capacity (15, 26, 28).

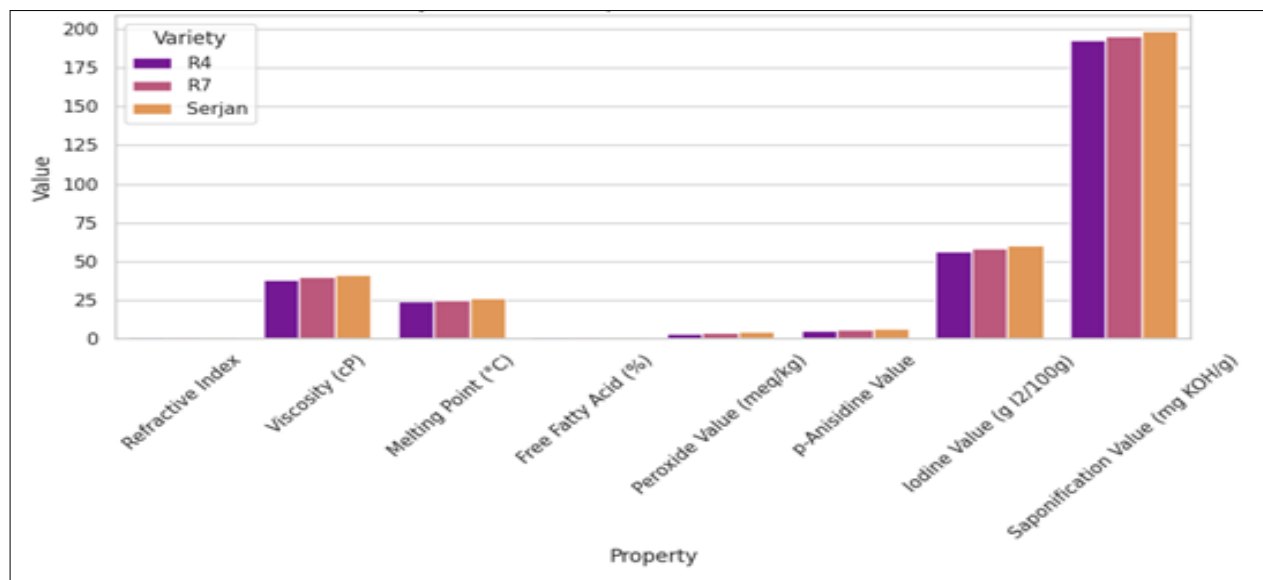
Physicochemical characteristics and quality parameters of rambutan seed oil

A study investigating the physicochemical properties of rambutan seed oil from three varieties, R4, R7 and Serjan (Table 1; Fig. 1), revealed no significant differences ($p > 0.05$) in colour, refractive index and viscosity among the varieties. This suggested a relatively stable compositional profile irrespective of the genotype. The oils exhibited a golden-yellow colour, with a red-to-yellow (R/Y) ratio of less than 0.3, indicating a predominantly yellow appearance. The refractive indices for R4, R7 and Serjan were 1.4647, 1.4631 and 1.4620, respectively, aligning with previous findings by (9). Similarly, viscosity measurements at 25 °C were 49.25, 50.40 and 50.95 cP for R4, R7 and Serjan, respectively, indicating fluidity comparable to that of other plant oils, primarily governed by factors such as molecular weight, melting point and degree of unsaturation (9). In contrast, melting points differed significantly ($p < 0.05$), with Serjan exhibiting a higher melting point (26.60 °C) than R4 (24.54 °C) and R7 (25.67 °C), which may be attributed to a greater proportion of high-melting triglycerides. This suggests that while most physicochemical traits are consistent among varieties, subtle differences in thermal behaviour may influence potential applications in food and industrial formulations. The study also evaluated the quality parameters of the oils, including free fatty acid (FFA) content and

Table 1. Physicochemical properties of rambutan seed oil extracted from three varieties (R4, R7, Serjan)

Property	R4	R7	Serjan
Colour	Golden Yellow (R/Y < 0.3)	Golden Yellow (R/Y < 0.3)	Golden Yellow (R/Y < 0.3)
Refractive Index	1.4647	1.4631	1.4620
Viscosity (cP at 25 °C)	49.25	50.40	50.95
Melting Point (°C)	24.54	25.67	26.60

NB: The table presents comparative data on colour, refractive index, viscosity and melting point, highlighting a consistent golden-yellow hue and subtle variations in thermal and flow characteristics among the varieties.

**Fig. 1.** Comparative analysis of physicochemical properties of rambutan seed oil across varieties R4, R7 and Serjan.

peroxide value (PV), which are crucial indicators of oil quality. The PVs for R4, R7 and Serjan were 2.00, 1.82 and 1.74 meq O₂ kg⁻¹ oil, respectively, significantly lower than the Codex Alimentarius Commission's maximum limit (29), suggesting good oxidative stability and long shelf life. The p-anisidine values (p-AV) were also low (0.66, 0.49 and 0.54), indicating minimal secondary oxidation products. The iodine values (IV) for R4, R7 and Serjan were 47.49, 46.00 and 44.26 g I₂ 100 g⁻¹ oil, respectively, indicating varying degrees of unsaturation, with R4 having the highest unsaturated fatty acid content (10). The saponification values (SV) were consistent across the varieties, aligning with reported values for rambutan seed fat (9).

Fatty acid profile, thermal behaviour and solid fat content

Fatty acid composition analysis identified 12 fatty acids, with oleic acid (37.75-40.58 %) and arachidic acid (34.75-36.89 %) being the major constituents, accounting for over 74 % of the total fatty acids. The oils also contained palmitic acid, stearic acid and gondoic acid in smaller amounts. Differential Scanning Calorimetry (DSC) thermograms showed distinct melting and crystallization peaks, with Serjan exhibiting higher crystallization and melting onset temperatures due to its higher saturated fatty acid content (10, 28). Solid Fat Content (SFC) profiles indicated that Serjan had the highest SFC across temperatures, attributed to its higher long-chain saturated fatty acid content (25). The findings suggest that rambutan seed oil is predominantly liquid at ambient temperature, making it suitable for various applications while demonstrating good oxidative stability and nutritional potential (30).

Bioactive compounds and pharmacological potential of Rambutan byproducts

Additionally, dried rambutan rinds have been used in traditional Malaysian medicine (14). These seeds are notably high in

polyphenols, which are astringent compounds, including anthocyanins (3 %), leucoanthocyanins (3 %), catechins (3 %) and complex polyphenols (31). The primary polyphenolic compounds identified in rambutan seeds are tannins and flavonoids, such as geraniin, corilagin and ellagic acid (32). These polyphenols possess various bioactivities, including antioxidant, anti-inflammatory and anticancer properties, suggesting they may offer health benefits and protection against chronic diseases such as cardiovascular disease, neurodegenerative disorders and cancers (33). Previous research has assessed the antioxidant and phenolic content of rambutan fruit peel and seeds. Compounds such as butylated hydroxytoluene (BHT), gallic acid, ellagic acid, corilagin and geraniin were extracted from the peel of *N. lappaceum*. The antioxidant properties of these isolated compounds were evaluated using lipid peroxidation inhibition and DPPH radical scavenging assays. Phytochemicals are being increasingly recognized in the field of healthy ageing as promising therapeutics against several ageing-related diseases (32).

According to a previously conducted study, rambutan seeds also contain antidiabetic compounds (34). These seeds are traditionally used by locals in Malaysia to manage blood sugar levels. Recent phytochemical analyses indicate that rambutan seeds and peels contain compounds such as geraniin, ellagic acid and corilagin -polyphenolic compounds known for their antioxidant and antidiabetic effects (28). Geraniin has been shown to inhibit the formation of Advanced Glycation End-products (AGEs), which are implicated in diabetic complications (35). Additionally, flavonoids such as quercetin and epigallocatechin-3-gallate (EGCG) present in rambutan extracts may enhance insulin secretion by stimulating pancreatic β -cells and improving insulin sensitivity via antioxidant-mediated pathways. Rambutan seeds and peels thus represent a promising source of functional bioactives with potential applications in managing diabetes and other chronic, oxidative stress-related

disorders. (35, 36)

Challenges and prospects

Rambutan stands out as a versatile tropical fruit with significant nutritional, medicinal and industrial importance, especially through its bioactive-rich seeds and peels. While studies highlight antidiabetic, antihypercholesterolemic and antioxidant effects, the precise pharmacological mechanisms underlying these effects remain largely unexplored. Additionally, most existing studies are confined to in vitro or animal models, leaving a significant gap in human-based research. The absence of clinical trials hinders the validation of efficacy, safety and dosage optimization for rambutan seed and peel extracts. Furthermore, while physicochemical analyses have positioned rambutan seed fat as a viable cocoa butter alternative, there is limited research on consumer acceptance, sensory evaluation and industrial scalability. The economic feasibility of processing rambutan by-products into functional ingredients or specialty fats also remains underexplored, particularly in low-resource settings where such innovations could have a substantial impact.

There is also a need to explore underutilized components of the fruit, such as the testa and embryo, which may harbour novel compounds with health-promoting properties. Integrating rambutan by-product valorization into circular economy frameworks could further enhance sustainability, reduce agricultural waste and support eco-friendly food production systems. By addressing these gaps, future studies can unlock the full potential of rambutan as a cornerstone of innovation in food science and health.

Conclusion

Rambutan (*Nephelium lappaceum* L.) by-products, particularly seeds and peels, represent valuable yet underexploited resources with significant potential for functional food, nutraceutical and industrial applications. The presence of diverse bioactive compounds, including phenolics, flavonoids and tannins, contributes to their demonstrated antioxidant, antimicrobial, antidiabetic and antihypercholesterolemic properties. In addition, the unique fatty acid composition of rambutan seed fat, characterized by high levels of oleic and arachidic acids, imparts favorable physicochemical properties such as desirable melting behavior, crystallization patterns and solid fat content, supporting its application as a potential cocoa butter alternative in confectionery systems.

Processing techniques, including fermentation and roasting, further enhance the sensory and functional qualities of rambutan seed-derived products, facilitating their utilization in cocoa-like formulations and value-added food products. Despite these promising attributes, the transition from laboratory-scale findings to industrial application remains limited. Key challenges include insufficient clinical validation, limited understanding of bioactive mechanisms and gaps in large-scale processing, economic feasibility and consumer acceptance.

Future research should prioritize in vivo and clinical investigations, optimization of processing technologies and standardization of product quality to enable commercialization. The integration of rambutan by-product utilization into sustainable and circular economy frameworks offers a viable pathway for reducing agro-industrial waste while generating high-value functional ingredients. Overall, rambutan by-products hold considerable

promise as sustainable alternatives in the evolving landscape of food science and technology.

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Authors' contributions

SMS wrote the original draft, reviewed and edited the manuscript, conducted the methodology and curated the data. RK reviewed and edited the manuscript and performed the methodology. JD supervised the work, created visualizations and conducted formal analysis. DS, SM, NKB, PKD and BY edited and analyzed the data. All authors read and approved the final manuscript.

Compliance with ethical standards

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