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Starch-Based Smart Food Packaging in Tropical Climates: A Review of Bibliometric Trends, Degradation Behavior, and Circular Economy

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Abstract

The global imperative to replace recalcitrant petrochemical plastics with biopolymer alternatives has directed increasing attention toward starch-based smart food packaging. This review synthesizes current knowledge across three interrelated domains: bibliometric trends, Degradation Behavior, and circular economy considerations, with a specific focus on tropical climates. A localized bibliometric analysis reveals a pronounced research emphasis on valorizing indigenous resources in major food-producing tropical nations, yet identifies critical gaps in climate-specific degradation studies, regulatory fragmentation, and limited multidisciplinary integration. Concerning Degradation Behavior, the high ambient humidity and elevated temperatures characteristic of tropical regions create a paradox: rapid post-disposal compostability is offset by compromised mechanical integrity and premature shelf life failure during use. This review examines advanced polymer blending and nanofiller strategies designed to balance functional stability with controlled hydrolytic breakdown. From a circular economy perspective, the analysis assesses alignment with the United Nations Sustainable Development Goals, the Malaysia Plastics Sustainability Roadmap 2021 to 2030, the National Agrofood Policy (NAP 2.0), and Halal certification (MS 1500:2019). By integrating material science, environmental management, and regulatory governance, this review highlights the necessity for synchronized frameworks to translate laboratory-scale innovations into commercially viable, climate-appropriate packaging solutions for developing bioeconomies.

Keywords : Smart packaging; Starch-based biopolymer; Bibliometric analysis; Tropical Degradation Behavior; Circular economy

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1.0 INTRODUCTION

The development of starch-based smart food packaging represents a critical innovation in addressing the environmental challenges posed by conventional petroleum-based plastics, particularly within the demanding conditions of tropical climates (Yu et al., 2026; Rashid et al., 2026; Arruda et al., 2025; Yudhistira et al., 2024). Moreover, the escalating ecological burden of single-use, non-biodegradable food packaging has driven exponential growth in the development of sustainable biopolymers, as depicted in **Figure 1(a)**. At the same time, the global mandate to ensure food security, which is anchored in United Nations Sustainable Development Goals like SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production), demands new technologies that significantly reduce food loss after the harvest. In this nexus of environmental and agricultural challenges, starch-based "smart packaging" emerges as a premier bio-circular solution. **Figure 1(b**) shows that by leveraging the global abundance and complete biodegradability of starch, material scientists have elevated conventional films into active paradigms (which interact continuously with the headspace environment via the controlled release of antimicrobials) and intelligent paradigms (which utilize dynamic sensors to communicate real-time food quality). These biopolymer-based systems offer renewability, biodegradability, and compostability, aligning with global sustainability goals (Rashid et al., 2026; Awobifa et al., 2026; Kusuma et al., 2024; Asrafali et al., 2026). However, their widespread adoption, especially in tropical regions characterized by high temperatures and humidity, is contingent upon overcoming inherent limitations in material properties, understanding Degradation Behavior, and navigating complex regulatory landscapes (Arruda et al., 2025; Cheng et al., 2021).

Starch, a natural polysaccharide, is abundant, low-cost, and possesses good film-forming properties, making it a promising alternative to synthetic polymers (Awobifa et al., 2026; Dos Santos et al., 2024; Asrafali et al., 2026). It is composed of two main polymers: the linear amylose and the branched amylopectin, with their structural differences dictating their physical properties and digestibility (Awobifa et al., 2026; Gonçalves et al., 2024; Vaz Matheus et al., 2023). For instance, amylose forms gels, while amylopectin acts as a thickener (Bangar et al., 2021). The glycosidic linkages in starch make it an easily digestible energy source (Huang & Wang, 2025). However, as shown in **Figure 1(c)**, unmodified starch films suffer from high hydrophilicity, low mechanical strength, and poor barrier properties, which restrict their application in food packaging, particularly where moisture sensitivity is a critical concern (Awobifa et al., 2026; Gonçalves et al., 2024; Kusuma et al., 2024; Liu et al., 2025). While laboratory innovations are prolific, the translational success of starch-based smart packaging is inextricably tied to regional environmental conditions and national policy architectures. Malaysia serves as an optimal microcosm for this transition. Characterized by high agricultural biodiversity, an equatorial climate, and a rapidly developing bioeconomy, the nation is actively restructuring its supply chains under the National Agrofood Policy 2021–2030 (NAP 2.0) and the National Food Security Policy Action Plan 2021–2025.

To enhance the functionality of starch-based packaging for smart applications, various modification strategies have recently been explored, as shown in **Figure 1(d)**. These include chemical modifications, polymer blending, and the incorporation of bio-nanocomposites such as cellulose nanofibers and montmorillonite (Gonçalves et al., 2024; Kusuma et al., 2024; de Oliveira et al., 2025; Sundaresan et al., 2025). Such enhancements aim to improve critical properties like tensile strength, flexibility, and barrier efficacy against gases and moisture (Rashid et al., 2026; Sundaresan et al., 2025). For example, integrating lignin into starch films can improve moisture barrier and mechanical properties by reducing their hydrophilic nature (Dutta and Sit, 2024; Liu et al., 2025). Similarly, nanostructured starch materials have been shown to produce films with stimuli-responsive capabilities and controlled release of functional ingredients, enabling intelligent packaging features (Engel et al., 2022; Tracey et al., 2022). Electrospinning is another technique that produces nano/micro fibres with high surface-to-volume ratios, suitable for encapsulating bioactive compounds and broadening starch applications in food packaging and additives (Martins Fonseca et al., 2024; Abedi-Firoozjah et al., 2022; Zhang et al., 2024)). **Figure 1** represents the overall concept of starch-based smart food packaging in tropical climates.

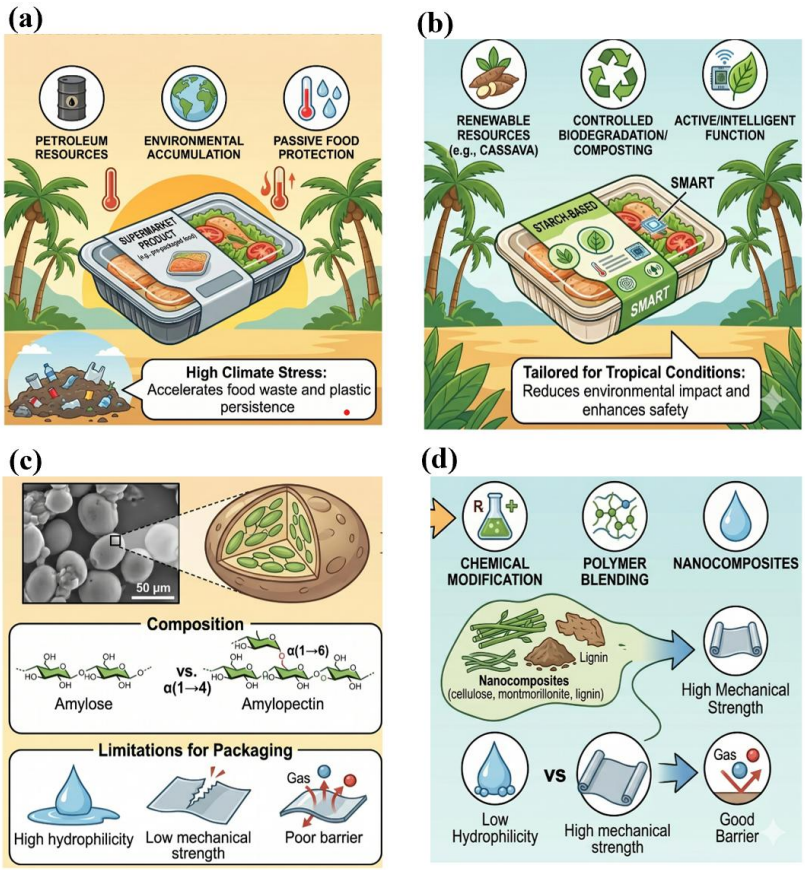


Figure 1 : The overall concept of smart packaging on starch includes (a) the environmental impact of conventional single-use packaging materials, (b) the innovation of starch-based "smart packaging", (c) the disadvantages related to native starch properties, and (d) current modification strategies on starch packaging.

The concept of "smart packaging" transcends traditional passive containment, integrating functionalities for real-time monitoring of food quality, enhanced food safety, and extended shelf-life (Kumar et al., 2025; Karnwal et al., 2025; Martins Fonseca et al., 2024; Yao et al., 2024). This includes active packaging, which directly interacts with the food or its environment to extend shelf life (e.g., by incorporating antimicrobial agents, oxygen scavengers, or moisture absorbers), and intelligent packaging, which monitors food conditions and communicates information about its quality or freshness (Kumar et al., 2025; Singh et al., 2024; da Silva Rocha et al., 2025; Akin et al., 2023). Polysaccharides, including starch, are highly promising materials for such intelligent packaging systems due to their advantageous properties (Martins Fonseca et al., 2024; Dani Nandiyanto & Dewi, 2022). Natural colorimetric indicators derived from pigments like anthocyanins, curcumin, and betalains are widely employed in biodegradable matrices, including starch, to provide pH- and gas-responsive sensing for real-time freshness assessment (Kumar et al., 2025; Madhu, 2025). The integration of artificial intelligence (AI) is further transforming smart packaging, enabling adaptive food-quality management and improved supply-chain efficiency (Karnwal et al., 2025). Notably, AI algorithms can process data from embedded sensors monitoring temperature, humidity, pH, and volatile compounds to predict spoilage, estimate remaining shelf life, and provide real-time quality assessments. Moreover, machine learning and predictive analytics facilitate optimized storage conditions, inventory management, and demand forecasting, thereby reducing food waste and enhancing the overall efficiency and sustainability of the food supply chain.

2.0 BIBLIOMETRIC ANALYSIS OF STARCH-BASED SMART FOOD PACKAGING

In this study, the bibliometric analysis was conducted using the Scopus database, with VOSviewer employed to generate visual maps of the research landscape, highlighting key publications, authors, keywords, and citation networks. We explored the development and application of starch-based smart food packaging by utilizing a structured query in Scopus. This query targeted titles, abstracts, and keywords using the specific search string ("smart packaging" OR "starch" OR "biopolymer" OR "packaging Film"), ensuring a comprehensive coverage of recent and relevant literature. The subject areas were refined to include Agricultural and Biological Sciences, Materials Science, Chemistry, Chemical Engineering, Environmental Science, and Multidisciplinary Studies, reflecting the inherently interdisciplinary nature of contemporary packaging research. The analysis

concentrated on articles and reviews to obtain detailed insights into prevailing trends, while limiting results to English-language publications to ensure broader accessibility. The initial search yielded 17,781 document records, underscoring a substantial and rapidly expanding body of literature focused on starch biopolymers and their applications in advanced packaging systems.

In particular, the bibliometric analysis reveals a growing interest in starch-based biodegradable polymers, particularly between 2021 and 2026, driven by the demand for sustainable alternatives to fossil-based plastics (Cheng et al., 2021). Countries such as China, India, and the United States have led research on starch-based plastics, with a notable increase in publications on cassava starch for food packaging over the last decade (Linan et al., 2024; Vaz Matheus et al., 2023). Overall, food packaging research within the food science and technology disciplines has shown continuous growth, underscoring its interdisciplinary nature and societal importance, particularly with respect to sustainability (Nordin et al., 2022). Research articles on active packaging systems for food packaging also showed a substantial increase, with an annual growth rate of 23.76%, highlighting global interest in this area (Dirpan et al., 2023; Murtaza et al., 2024). Furthermore, the bibliometric analysis presented in **Figures 2(a–d)** provides a critical foundation for understanding the research landscape on starch-based smart food packaging, particularly in tropical climates. In particular, the VOSviewer network (**Figure 2(a)**) reveals that the thematic structure of starch-based food packaging research is heavily dominated by material properties, with repeated high-frequency terms such as packaging material, mechanical properties, thermal stability, chemical composition, and stress resistance. The substantial redundancy in packaging/packing material entries (over 15 occurrences) indicates both the centrality of material science in this domain and a potential lack of terminological standardization in the literature. Notably, keywords directly associated with tropical climate conditions (e.g., humidity, high temperature, microbial load), degradation behavior (e.g., hydrolysis rate, plasticizer migration, diffusion coefficients), and regulatory frameworks (e.g., food contact materials legislation, biodegradability certification) are either absent or weakly represented. This gap suggests that, although extensive research exists on the physicochemical characterization of starch-based materials, relatively few studies have explicitly integrated tropical environmental stressors into their experimental designs or considered region-specific regulatory requirements. For a review focused on smart packaging in tropical climates, this finding justifies the need to synthesize fragmented knowledge across materials science, environmental engineering, and food safety regulation.

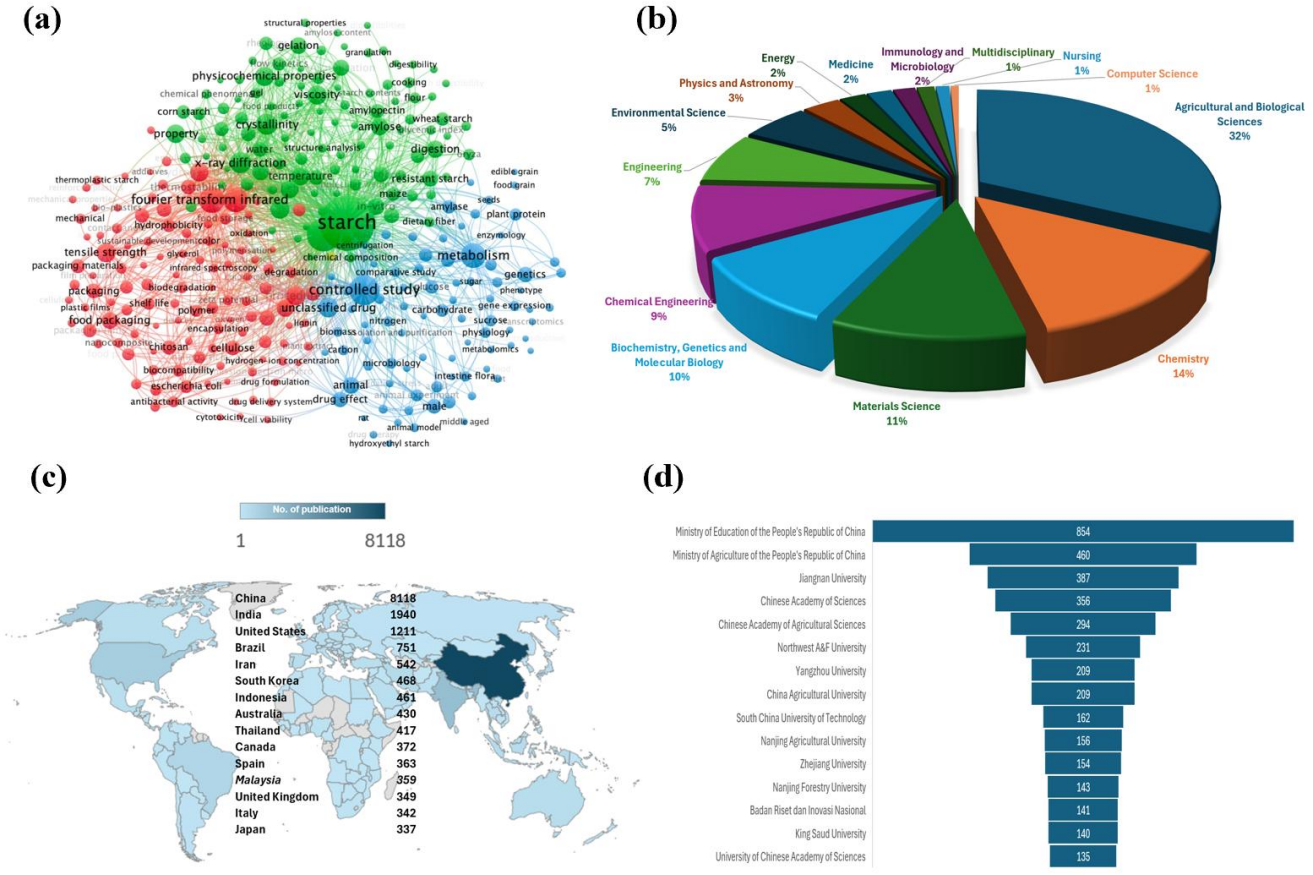


Figure 2 : Bibliometric analysis using VOSviewer from Scopus for (a) Central network links focus on co-occurrence patterns on starch-based food packaging, (b) Distribution (%) on merging research areas, (c) Map on countries with related published articles, and (d) Top 15 affiliated funding sources that supported the published articles.

Figure 2(b) demonstrates that the literature is overwhelmingly concentrated in Agricultural and Biological Sciences (32%), with much smaller percentages in Medicine (2%), Microbiology (1%), Multidisciplinary (1%), and Computer Science (1%). This distribution reveals a critical disciplinary silo problem. Smart packaging for tropical climates requires convergence of four areas: (i) polymer degradation behavior from chemical engineering, (ii) microbial spoilage patterns in warm and humid conditions from food microbiology, (iii) sensor response stability from materials physics, and (iv) risk assessment for migrant compounds from toxicology. The near absence of Microbiology at only 1 % and the lack of any representation in Environmental Science or Toxicology suggest that current research rarely adopts the integrated approach needed for tropical applications. Furthermore, the negligible contribution from Computer Science at 1 % indicates limited adoption of predictive modeling, such as machine learning for degradation prediction or shelf life estimation under dynamic tropical conditions, representing a missed opportunity for advancing smart packaging design. The country map (**Figure 2(c)**) shows an extreme disparity in publication volume, ranging from a minimum of 1 article to a maximum of 8,118 articles (presumably from China, given the funding source data in Figure d). While the specific countries are not labeled in the provided extract, the range indicates that a single nation dominates global research output on starch-based packaging. This concentration raises important considerations for tropical climate applications. First, a geographic mismatch exists. Most major food-producing tropical nations, such as Indonesia, Brazil, Nigeria, Thailand, Vietnam, and India, are not necessarily the leading publishers. If the top producer is a temperate or subtropical country, for example, China, the United States, or European nations, much of the existing literature may have been generated under environmental conditions of moderate temperature and low relative humidity that do not replicate tropical stress. Second, limited local research capacity is evident. **Figure 2(d)** reveals overwhelming dominance by Chinese institutions and funding agencies: the Ministry of Education of the People's Republic of China (854 publications), the Ministry of Agriculture (460), Jiangnan University (387), the Chinese Academy of Sciences (356), and multiple other Chinese universities collectively account for 12 of the top 15 positions. Only three non-Chinese entities appear: Badan Riset dan Inovasi Nasional (Indonesia, 141), King Saud University (Saudi Arabia, 140), and University of Chinese Academy of Sciences (135—note that this is still China-affiliated, leaving essentially only two truly international entries). The presence of Badan Riset dan Inovasi Nasional (Indonesia) in **Figure 2(d)** suggests some tropical country participation, but its ranking, 13th with 141 publications, is substantially lower than that of Chinese institutions. This gap implies that degradation behavior and regulatory frameworks specific to tropical climates may be understudied due to limited funding and research infrastructure in the regions most in need of such solutions.

As evidenced in the bibliometric analysis, this funding landscape reveals three major research gaps that justify the present review. First, degradation behavior studies on starch-based materials are almost exclusively conducted under standard laboratory conditions, such as 25°C and 50% relative humidity, rather than under real-world tropical cycling, including diurnal temperature fluctuations of 25 to 35°C, high humidity, intense UV exposure, and elevated microbial pressure. Second, the dominance of Chinese funding agencies means the regulatory perspective in the literature primarily reflects China's food contact material standards, while tropical countries often operate under distinct frameworks, such as ASEAN guidelines or Brazil's ANVISA resolutions, creating a regulatory fragmentation that a comprehensive review must address. Third, the negligible representation of microbiology, computer science, and medicine in the bibliometric data indicates limited multidisciplinary integration, which hinders the validation of smart packaging functionalities, such as freshness indicators and antimicrobial release systems, under actual tropical supply chain conditions. Collectively, these gaps underscore the need to critically evaluate existing kinetic models, compare regulatory benchmarks across tropical and temperate regions, and highlight opportunities for predictive modeling and microbial risk assessment in smart packaging design. The VOSviewer analysis confirms that starch-based food packaging is a materially-focused, geographically concentrated research field with limited integration of tropical climate parameters, degradation behavior under realistic conditions, or region-specific regulatory considerations. For a review titled "Starch-Based Smart Food Packaging in Tropical Climates", these bibliometric findings serve both as a justification (the field lacks tropical-focused synthesis) and a roadmap (identifying where the review must extend beyond existing literature). The subsequent sections of this manuscript will therefore prioritize: (i) extraction of degradation kinetic data from studies conducted under high-humidity and high-temperature conditions, even if sparse; (ii) comparative analysis of regulatory frameworks across major tropical food-producing regions; and (iii) recommendations for standardizing environmental testing conditions to reflect tropical supply chains.

To complement the Scopus database, the retrieved data from the Web of Science (WOS) database were exported and then imported into the Bibliometrix package for R (version 4.3.3) to perform bibliometric and scientometric analyses and to generate the visualizations shown in **Figure 3**. The keyword co-occurrence network establishes the foundational core of this research domain, heavily centered around nodes such as "starch," "edible films," and "mechanical properties," which are critical to the development of starch-based smart food packaging in **Figure 3(a)**. Within the context of tropical climates, these central nodes highlight a primary engineering challenge: formulating biocomposites, often by blending starch with polymers like chitosan, that can maintain their structural integrity under extreme environmental stress. The dense clustering and thick connecting lines between "physicochemical properties" and "water vapor permeability" demonstrate that researchers are acutely focused on optimizing these materials against the high humidity and elevated temperatures characteristic of tropical regions, ensuring the packaging remains robust while actively monitoring or preserving food quality. In **Figure 3(b)**, the thematic evolution from 2013 to 2026 illustrates a strategic shift in research priorities that directly addresses the complex degradation behavior of

these biopolymers. Early literature before 2019 was dominated by fundamental investigations into water vapor permeability, a critical variable that dictates how rapidly starch-based films degrade when exposed to tropical moisture. As the field matured through 2021, the focus expanded toward broader structural characterizations, such as overall "barrier properties" and "physical properties," reflecting an effort to precisely control this degradation process (**Figure 3(c)**). Recent trends emphasize end-use applications such as "shelf life" and advanced "films," indicating a transition toward actively managing degradation behavior so that smart packaging performs reliably throughout its intended lifespan before safely breaking down. Reinforcing these trends, the word cloud visually underscores the monumental scientific effort required to overcome the inherent vulnerabilities of natural polymers in harsh climates. The massive scale of terms like "mechanical properties," "barrier properties," and "physical properties" relative to specific base materials like "thermoplastic starch" highlights the ongoing struggle to fortify these films against rapid environmental breakdown. For smart packaging deployed in tropical environments, achieving exceptional barrier performance is non-negotiable to prevent premature failure. Furthermore, the visible presence of terms related to antimicrobial and antioxidant properties hints at the integration of "smart" functional features, which must be carefully balanced with the mechanical demands of the packaging to protect perishable goods effectively in hot, humid conditions. Finally, the TreeMap in **Figure 3(d)** quantifies this research landscape, revealing that structural and barrier properties collectively constitute nearly a quarter of the mapped domain, while foundational materials and "edible films" hold significant individual shares (Wang et al., 2024). While the current bibliometric data is predominantly weighted toward material characterization and performance metrics, the successful commercialization of these smart packaging solutions ultimately hinges on stringent regulatory frameworks. As the literature increasingly pivots toward practical application, food safety, and shelf-life extension, future research must inextricably link these optimized degradation profiles and advanced barrier technologies with regional regulatory compliance. Navigating these frameworks will be essential to transition starch-based smart packaging from a laboratory concept into a viable, sustainable solution for the tropical market.

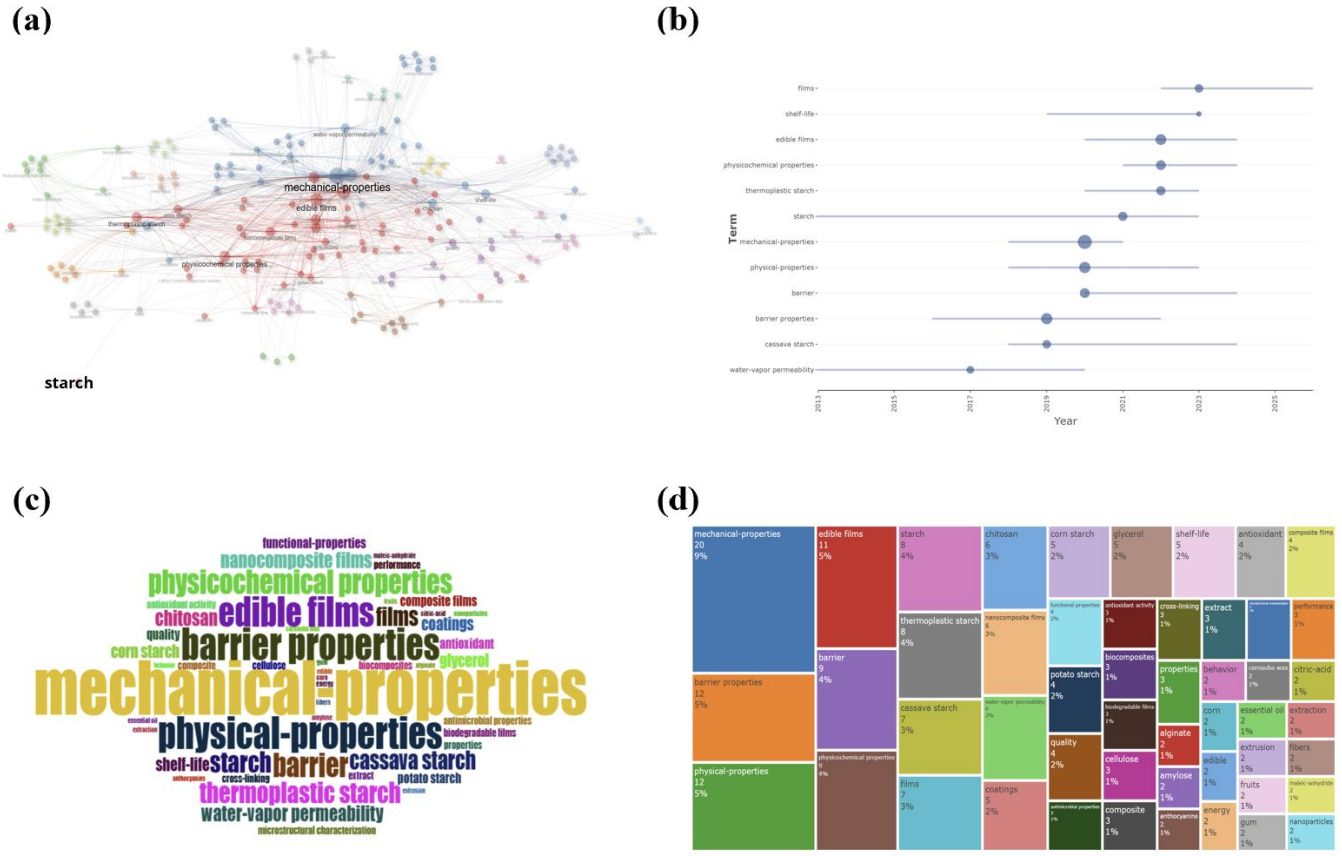


Figure 3 : Web of Science (WOS) knowledge domain map analysis (a) keywords from the co-occurrence network, (b) thematic trends from 2013 to 2026, (c) the word cloud, and (d) the trend topic illustrated by a TreeMap.

To validate these findings, the scientometric visualization of starch-based biopolymers and smart packaging **in Figure 4** reveals a field actively transitioning from fundamental material science toward high-value, sustainable applications. The strategic quadrant (**Figure 4(a)**) maps this thematic evolution using spatial centrality and density metrics; notably, the massive visual footprint of nodes like "edible films" and "physical-properties" represents a dominant publication volume, establishing

them as highly developed motor themes compared to the smaller, lower-frequency nodes of emerging niches like nanoparticles. This thematic hierarchy is further quantified by the topic dendrogram (**Figure 4(b)**), where short vertical branching distances reveal a high statistical frequency of term co-occurrence, dividing broad concepts into tightly clustered, specialized research niches involving starch blends and chemical modifications. The high volume of knowledge flow driving these advancements is captured in the Sankey plot (**Figure 4(c)**), where the substantial thickness of the interconnecting bands illustrates a concentrated, robust citation network passing from foundational polymer works, through prolific researchers, into dominant keywords like "food packaging." Furthermore, the chord diagram (**Figure 4(d)**) synthesizes this trajectory; the extended outer arc lengths for "starch" and "biopolymer" underscore their quantitative majority in the literature, while the thick inner chords heavily link them to "smart packaging" and "barrier properties." Overall, the quantitative convergence of these visual metrics definitively points toward a paradigm shift, demonstrating that foundational starch biopolymer research is rapidly being channeled into the high-volume, application-driven development of intelligent and sustainable food packaging systems.

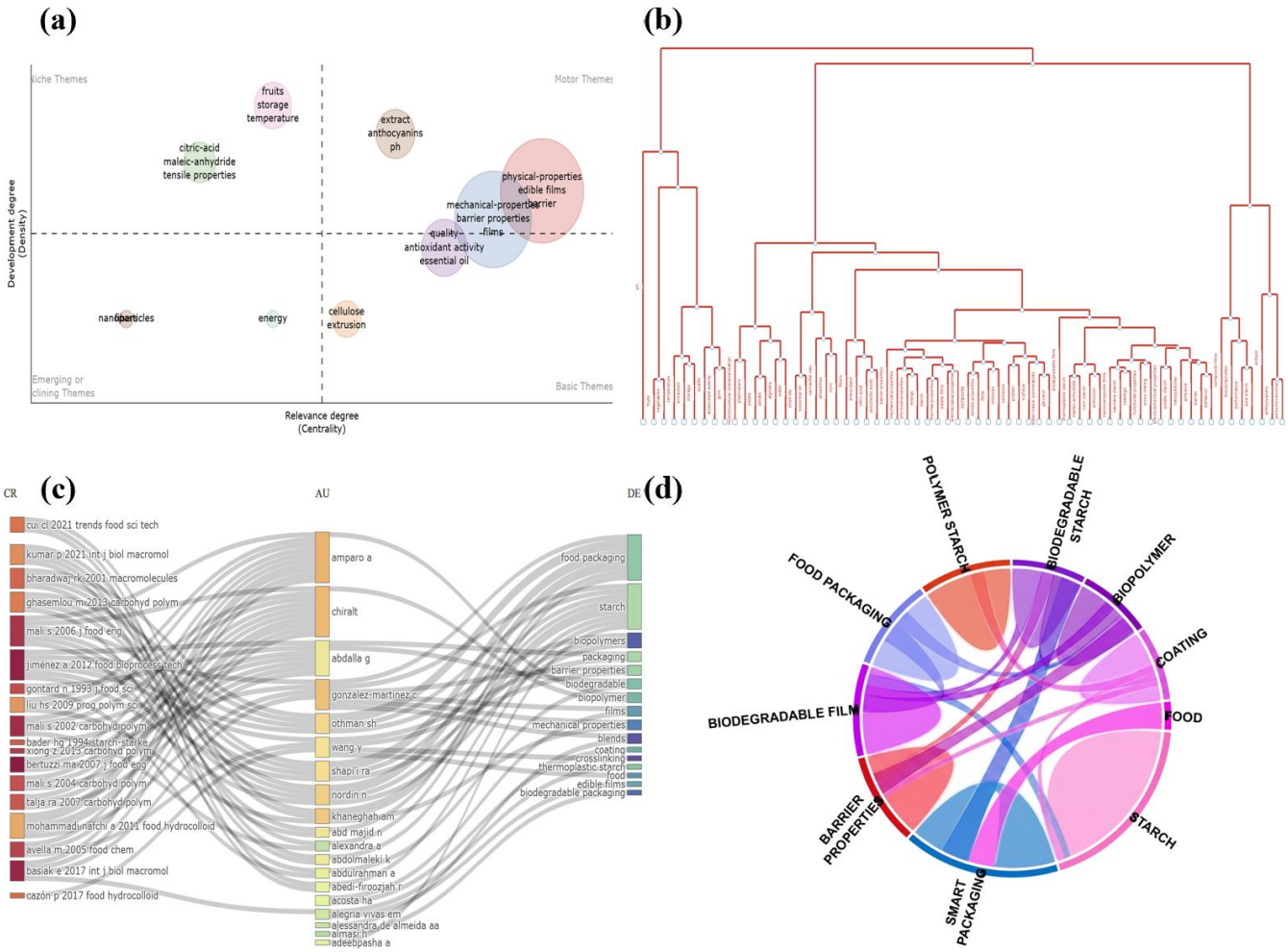


Figure 4 : Scientometrics visualization analysis (a) development against relevance for strategic quadrant, (b) topic dendogram, (c) Sankey plot illustrating the interconnectivity between prominent works (left), researchers (middle), and specific keywords (right), and (d) Chord diagram for the title search on “starch biopolymer” and “smart packaging”.

3.0 STRUCTURAL ANALYSIS ON DEGRADATION BEHAVIOR OF STARCH-BASED SMART PACKAGING FILMS

To accurately model the degradation behavior of starch under tropical climate conditions, this study adapted a cubic simulation box containing amylose and water molecules (**Figure 5(a)**), as described in our previous work (Matmin et al., 2023). This adaptation is essential because the high humidity and elevated temperatures characteristic of tropical regions directly influence water-polymer interactions and hydrolytic breakdown, which are critical factors for predicting the functional lifespan of starch-based smart food packaging. Nevertheless, tropical climates pose unique challenges for food packaging due to

persistently high temperatures and humidity, which accelerate microbial growth and food spoilage (Arruda et al., 2025). These conditions also influence the degradation behavior of biodegradable polymers like starch. A polymer's biodegradability is defined by its chemical backbone, particularly the presence of susceptible linkages such as esters (Huang & Wang, 2025). The mode of degradation can be either uniform bulk erosion or layer-by-layer surface erosion, dictated by the competition between water diffusion and the chemical reaction rate (Huang & Wang, 2025). The degradation rate is tunable through chemical factors (e.g., bond type, pH) and physical properties (e.g., crystallinity, glass transition temperature) (Huang & Wang, 2025).

The molecular electrostatic potential (MEP) analysis was performed to visualize the charge distribution across the surface of alpha-maltotriose, which serves as the simplest representative unit of starch, in **Figure 5(b)-(c)**. The optimized structure of alpha-maltotriose was obtained using Gaussian 16W software with the RB3LYP functional and the 6-31G(d) basis set. The final optimization yielded an electronic energy of –1908.611065 Hartree and a dipole moment of 4.111 Debye, indicating moderate polarity and an asymmetrical charge distribution, as shown in **Figure 5(b)**. The MEP map was generated from the total self-consistent field (SCF) electron density using an isosurface value of 0.0004, and the electrostatic potential was projected onto the molecular surface. The electrostatic potential values ranged from –0.07073 atomic units (red) to +0.07073 atomic units (blue), with a surface map value centered at –0.01556 atomic units (**Figure 5c**). The red regions represent electron-rich zones, typically localized around the oxygen atoms of hydroxyl groups, indicating nucleophilic character. In contrast, the blue regions correspond to electron-deficient areas, often near hydrogen atoms or less electronegative carbon centers, suggesting electrophilic behaviour. These features confirm the polar nature of alpha-maltotriose and its capacity for hydrogen bonding, which underpins water-driven degradation behavior in starch-based smart food packaging under tropical humidity. **Figure 5(d)-(e)** shows the number density maps of glucan (GLC) and solvent (SOL) molecules, respectively, within the amylose complex cavity. The GLC number density map (**Figure 5d**) illustrates the spatial distribution of amylose chains, while the SOL number density map (**Figure 5e**) tracks water penetration. The overlapping high-density regions indicate that water molecules successfully infiltrate the amylose matrix, leading to fragmentation of the complex (orange zone). Together, these maps confirm that water acts as a dissociating solvent, strongly interacting with glucan chains and reducing interchain hydrogen bonding, a critical step in the hydrolytic degradation of starch-based packaging in tropical climates.

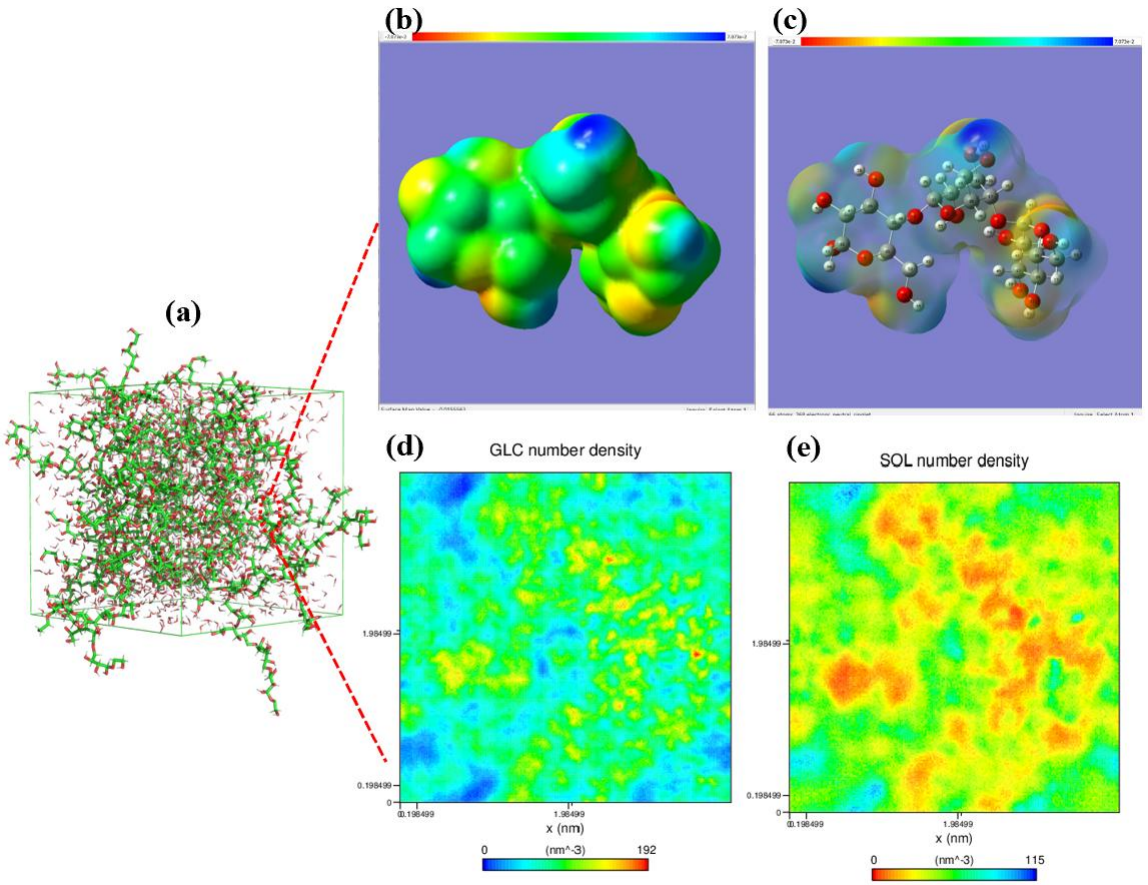


Figure 5 : Starch structural analysis based on (a) cubic simulation model, (b) MEP charge distribution across the surface, (c) structural distribution based on the simplest optimised unit, (d) spatial distribution, and (e) water molecule penetration on the amylose-to-water system.

For starch-based materials, high moisture content can compromise their integrity, as demonstrated by the degradation of waxy corn starch by gaseous hydrogen chloride, which is affected by moisture levels (Lin et al., 2024). The environmental fate of biodegradable polymers is highly context-dependent, varying significantly between controlled industrial composting, cooler soil, or aquatic environments (Huang & Wang, 2025; Janika et al., 2025). In tropical environments, the elevated temperatures and humidity can lead to faster degradation compared to temperate zones. For a material to be certified as "compostable," it must degrade within a specific timeframe under defined conditions, which includes meeting industrial composting standards such as EN 13432 or ASTM D6400 (Janika et al., 2025). These standards require a high percentage of organic carbon conversion to CO_2 (at least 90%) within 180 days in a controlled thermophilic composting test (Janika et al., 2025). The breakdown of these materials is a microbially mediated process (Huang & Wang, 2025). For example, poly(vinyl alcohol)/starch-based fertilizers have been studied for their biodegradation and nutrient release profiles, demonstrating the interaction of these materials with soil microbiota (Dos Santos et al., 2024).

4.0 TRANSITIONING STARCH-BASED SMART PACKAGING INTO A CIRCULAR ECONOMY

A critical dimension in evaluating the viability of starch-based smart food packaging is its alignment with circular economy (CE) principles, particularly in tropical climates where environmental conditions and waste management infrastructure significantly influence material performance. According to the Ellen MacArthur Foundation's core principles of eliminating waste, keeping materials in use, and regenerating natural systems, starch-based packaging must be viewed not merely as a plastic alternative but as an integrated component of the material, food, and environment system. From a systems perspective, this requires integrating methodologies like Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) to evaluate the material's entire lifespan, from feedstock sourcing and processing to functional use and end-of-life fate.

At the beginning of this life cycle, starch-based materials offer the advantage of utilizing renewable biogenic carbon. However, circularity is not automatically achieved at the feedstock stage. Large-scale starch production can introduce trade-offs involving agricultural land use, water consumption, and competition with food supply chains. To mitigate these upstream environmental and socio-economic pressures, a truly circular approach must prioritize the utilization of non-food biomass, agricultural residues, or industrial starch waste streams. Assuming sustainable sourcing is achieved, the next hurdle is maintaining functional integrity without compromising degradability. In tropical regions, biogenic starch often requires mechanical and barrier enhancements—such as polymer blending or nanofillers—to withstand heat and humidity. This creates a "circularity paradox," where the increased durability required for the packaging's use phase complicates its post-consumer recovery. To maintain a closed-loop system, material innovation must prioritize mono-material designs and biocompatible additives that safely reintegrate into the biosphere without disrupting land-use ethics.

Despite these material challenges, integrating active and intelligent functionalities (*viz*. oxygen scavengers or pH-sensitive freshness indicators) serves as a powerful tool for waste reduction. In tropical climates where high temperatures accelerate spoilage, the environmental benefits of extending food shelf life often outweigh the added material complexity of the sensors. By preventing food loss, these smart systems align with CE principles by maximizing the value of resources within the food supply chain, effectively offsetting the carbon footprint of the packaging's production. Yet, the environmental promise of these smart materials is frequently undermined by a disconnect between laboratory certifications (e.g., EN 13432) and the infrastructural realities of tropical nations. In the absence of industrial composting facilities, "biodegradable" plastics often default to landfills or open environments where their breakdown is inconsistent. Furthermore, while high ambient humidity can accelerate degradation, it simultaneously risks premature packaging failure during the use phase. Achieving genuine circularity demands locally adapted strategies focused on home-compostable and soil-degradable systems that ensure complete mineralization within regional ecological constraints. The overall CE of starch-based smart packaging roadmap can be represented in Figure 6.

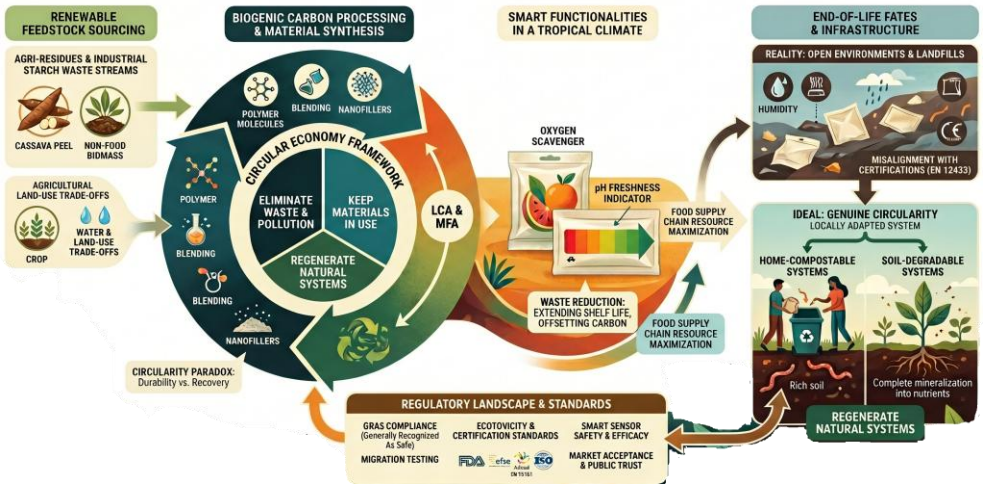


Figure 6 : Roadmap on the CE of tropical starch-based packaging materials.

More importantly, navigating these complex functional and infrastructural demands ultimately requires a robust regulatory framework. While regulations for novel and smart packaging vary across jurisdictions, establishing stringent standards is paramount for market acceptance and public trust. For example, emerging benchmarking practices—such as those investigated by Ghana's food industry (Rahman et al., 2025)—highlight the necessity of regulatory compliance. Foundational food safety standards, like the "Generally Recognized As Safe" (GRAS) designation, must apply not only to ingredients but also to packaging extraction processes and materials (Bhatlawande et al., 2023). Crucially, smart sensors and biodegradable polymers must undergo rigorous evaluation for chemical migration into food, physical disintegration rates, and post-disposal ecotoxicity (Huang & Wang, 2025; Janika et al., 2025; Song et al., 2022; Yu et al., 2024). Only by passing these stringent safety and efficacy requirements can starch-based smart packaging be recognized as truly circular and environmentally safe.

5.0 CONCLUSION

This review critically examined starch-based smart food packaging through bibliometric trends, Degradation Behavior, and circular economy principles, with a focus on tropical climates. The findings show that while global research momentum is strong, most studies optimize materials under generalized laboratory conditions, overlooking tropical stressors such as persistent high humidity, elevated temperature, and intense microbial activity. Bibliometric analysis confirms a geographically concentrated research landscape, with tropical nations underrepresented despite their greater need for these technologies. A pronounced disciplinary imbalance exists, favoring physicochemical characterization while lacking integration of microbiology, predictive modeling, and regulatory science.

The central paradox governing starch-based packaging in tropical climates is that the same hydrophilic structure enabling rapid biodegradation also causes premature moisture-induced failure during use. Molecular modelling confirms that water penetration into glucan matrices accelerates hydrolytic degradation under tropical conditions. Reinforcement strategies such as polymer blending and nanofiller incorporation improve mechanical integrity, but achieving the optimal balance between in-use stability and post-use degradability remains unresolved. From a circular economy perspective, genuine circularity requires systems-level integration of sustainable feedstocks, region-specific end-of-life infrastructure, and regulatory harmonization, rather than relying solely on biogenic origin or biodegradability.

Future research should prioritize standardized degradation testing under real tropical conditions, predictive computational models for humidity temperature coupling, multidisciplinary validation of smart functionalities, use of non-food feedstocks, and harmonized tropical regulatory frameworks. Starch-based smart food packaging offers a promising pathway for sustainable food preservation in tropical bioeconomies, but successful commercialization depends on the coordinated convergence of molecular engineering, environmental infrastructure, policy governance, and industrial scalability. Only then can it evolve from a laboratory innovation into a climate-adaptive, circular solution for tropical food packaging systems.

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