Trop J Nat Prod Res, November 2025; 9(11): 5253 - 5266
ISSN 2616-0684 (Print)
ISSN 2616-0692 (Electronic)

Tropical Journal of Natural Product Research

Available online at https://www.tjnpr.org

Review Article

Advances in Starch Modification: A Recent Systematic Review of Structural Innovations, Digestibility Enhancement, and Functional Applications in Food Systems

Nur H. Malik*, Norazlin Abdullah, Gan S. Ling

Faculty of Applied Sciences and Technology, Universiti Tun Hussein Onn Malaysia (UTHM) Pagoh Campus, 84600 Muar, Johor, Malaysia.

ARTICLE INFO

Article history:
Received 21 July 2025
Revised 02 October 2025
Accepted 21 October 2025
Published online 01 December 2025

ABSTRACT

Modified starch has emerged as a highly versatile ingredient in food manufacturing, valued for its ability to improve product quality, stability, and consumer acceptance. This systematic review examines recent advances in starch modification with emphasis on structural innovations, digestibility enhancement, and functional applications in food systems. Starch modification is essential for overcoming limitations such as undesirable texture, restricted digestibility, and poor processing stability. Despite its established role in food production, continued refinement of modification strategies is required to ensure functionality, health benefits, and sustainability in diverse applications. The review followed the PRISMA framework, using advanced searching strategies in Scopus and ScienceDirect databases. From this process, a total of 31 primary studies were identified and categorised into three central themes: (1) advancements in starch modification techniques, (2) starch digestibility and functional properties, and (3) functional applications in food systems. Findings indicate significance progress in modification techniques including enzymatic, chemical, and physical approaches, which have contributed to improved starch structure, functionality, and processability. Modified starches have also been shown to enhance digestibility, support controlled energy release, and improve food texture, mouthfeel, and shelf stability. Moreover, their application in a wide range of food products highlights their potential to deliver both technological advantages and health-related benefits. In conclusion, this review highlights the importance of continuous innovation in starch modification. Advancements in this area will be pivotal in designing food systems with superior functional properties, enhanced nutritional quality, and greater sustainability to address the evolving challenges of the global food industry.

***Keywords**:* Modified starches, Functional properties, Starch digestibility.

Introduction

Starch is a crucial polysaccharide found abundantly in many staple foods such as rice, wheat, maize, and potatoes. It serves as an important source of energy and a critical ingredient in various food products. In food systems, starch is valued for its ability to influence texture, stability, and viscosity, making it a versatile ingredient in numerous food products.[23,26,31,49,74] However, native starch has certain limitations, such as poor digestibility, susceptibility to retrogradation, and instability during food processing and storage.[3,7,46] These limitations have prompted significant interest in starch modification, a technique that alters the chemical structure or physical properties to enhance its functionality. Starch modification has emerged as an essential technique for improving the texture, digestibility, and nutritional profile of food products, addressing both consumer demands and health concerns. Recent research has made significant strides in starch modification, particularly in the areas of structural innovations and digestibility enhancement.

*Corresponding author. Email: nurhafizah@uthm.edu.my
Tel: +60 18-2922446

Citation: Malik NH, Abdullah N, Ling GS. Advances in Starch Modification: A Recent Systematic Review of Structural Innovations, Digestibility Enhancement, and Functional Applications in Food Systems. Trop J Nat Prod Res. 2025; 9(11): 5253 – 5266 https://doi.org/10.26538/tjnpr/v9i11.1

Official Journal of Natural Product Research Group, Faculty of Pharmacy, University of Benin, Benin City, Nigeria

Various methods such as physical treatments (e.g., extrusion, steam treatment, non-thermal processes),[5,17,45,53,72] chemical processes (e.g., acid or enzymatic hydrolysis),[44,65,67,70] and enzymatic modifications (e.g., dextrinization, crosslinking), have been extensively explored.[9,48,68,81] These approaches aim to improve the starch's functional properties, including its ability to form gel-like structures, its digestibility profile, and its interaction with other food components. For instance, studies have demonstrated that starch modification can lead to the development of low-glycemic index products which are increasingly sought after due to growing health concerns related to high blood sugar levels.[27,29,30,77] Furthermore, starch modifications have shown promise in improving the texture and sensory attributes of gluten-free products, addressing the needs of a growing population with gluten sensitivities or intolerances. Despite these advancements, several gaps remain in the existing literature on starch modification. One primary challenge is inconsistent outcomes arising from different modification techniques, influenced by starch source, modification method, and specific food application.[39,63,70] This variability raises questions regarding the general applicability and scalability of laboratory-based results for industrial applications. While much research has been focused on improving digestibility and reducing the glycemic index, limited attention has been addressed to the long-term health implications of consuming modified starches. As these starches become increasingly prevalent in processed foods, further research is needed to explore their impact on human health, particularly in relation to the gut microbiota and metabolic responses. Another unresolved issue in starch modification research is the lack of a comprehensive understanding of the interactions between modified starches and other food ingredients. The interactions between starch and proteins, fats, and other carbohydrates in food matrices can significantly affect the texture, stability, and nutritional properties of the final product.[10,47,56] However, research examining these interactions, particularly in complex food systems, remains limited. This knowledge gap presents challenges in

 ISSN 2616-0684 (Print)
ISSN 2616-0692 (Electronic)

scaling up starch modification techniques for large-scale production and ensuring consistency across different food products. To address the challenges and gaps identified above, this article presents a systematic review of recent advances in starch modification in the food system for its potential benefits, with a focus on structural innovations, digestibility enhancement, and functional applications in food systems. The primary objective is to examine how different starch modification techniques influence the structural properties, digestibility, and overall functionality of starch in various food applications. By synthesizing the most current research, the article aims to provide a clearer understanding of the benefits and limitations of starch modification and to identify areas where further investigation is required.

In addition, this review offers insights into the practical applications of starch modification in food product development, particularly for enhancing the health profiles and functional properties of food products. By addressing existing challenges and exploring the potential of modified starches, this review seeks to inform future research directions and foster innovation in the food industry, ensuring starch modification's ongoing contribution to healthier, and more sustainable food systems.

Literature Review

Starch modification techniques have been extensively studied to enhance the functional properties and digestibility of starches, which are crucial for their application in food and non-food industries. Various methods including physical, chemical, and enzymatic modifications have been explored to alter the structural and physicochemical properties of starches. For instance, extrusion, a widely used processing in snack production, can enhance the digestibility of starch by transforming the crystalline structure of starches from A-type to V-type, which is associated with a decrease in molecular weight and an increase in short-chain amylopectin content.[19,35] Such structural changes are crucial for modifying the glycemic index and digestive speed of starches, making them more suitable for specific dietary needs. The dual retrogradation-annealing modification technique applied to rice starches has demonstrated enhanced thermostability and enzyme resistance, which are desirable properties for both food and non-food applications.[28] Non-thermal techniques such as ultrasound have also demonstrated promise in improving starch's functional characteristics without significantly compromising its nutritional quality.[66,72] Ultrasonication has been shown to change disruption points in pea starch chains and an enlarge the molecular weight of linear chains. This modification enhanced the complexing ability of starch with lauric acid.[73] While these methods are effective, challenges remain in scaling them for industrial applications, particularly due to cost implications and the variability of outcomes depending on the source of the starch.[72]

In addition to physical and enzymatic approaches, chemical modifications have also played a significant role in tailoring starch properties for specific applications, including acid hydrolysis, oxidation, and crosslinking. These techniques exploit the various hydroxyl groups present in the starch granule to add a new functional group, which alters the gelatinization, pasting and retrogradation properties.[70] Acid-modified starches, for instance, have shown decreased crystallinity and improved water absorption capacity, making them suitable for use in reconstituted food products.[44] Crosslinking, on the other hand, has gained traction in the production of starch-based bioplastics, owing to its ability to improve mechanical and thermal stability.[1] Nevertheless, esterified starches have been widely studied in food applications which involves the use of organic acids including acetic, lactic, citric, and malic acids. Findings from previous studies suggest that the digestibility of native starches reduces after being treated with organic acids. This could be due to steric hindrance that limits the action of digestive enzymes in the small intestine.[12,14,16] These chemical approaches often yield starches with tailored properties suited for specific food applications. However, the environmental impact of chemical modifications, particularly in terms of waste generation and potential toxicity, remains a concern.[4,7,36]

Building on recent advances in chemical modification, as a more sustainable alternative, enzymatic modifications such as dextrinization and the application of amylase have been explored. These methods are not only eco-friendly but also allow for more precise control over the modification process, which is critical for producing consistent results across different batches of starch.[48,68,81] The application of 1,4-α-glucan branching enzyme in corn starch, for example, has been shown to increase the glycosidic linkage ratio and cyclic glucan content, resulting in a significant reduction in in vitro digestibility.[50] This method not only enhances the nutritional profile by increasing resistant starch content but also offers potential for industrial applications in producing slowly digestible starchy foods. Similarly, dual enzyme modification of oat starch using β-amylase and transglucosidase increases the resistant starch content and alter the crystalline structure, contributing to reduced digestibility.[59] The use of branching enzymes like AqGBE in potato starch modification also increases the resistant starch content significantly. This method alters the granule structure and increases the proportion of α-1,6-linked branches, thus enhancing the nutritional value by increasing the resistant starch fraction.[28] Similarly, amylosucrase modification of waxy corn starch has been reported to change its crystalline structure from A-type to B-type, leading to an increase in resistant starch content and a decrease in digestibility.[79] These enzymatic modifications are crucial for developing starch derivatives with improved nutritional profiles.

Modified starches have also garnered attention for their role in improving the nutritional profile of food products. With the increasing prevalence of metabolic disorders like diabetes, there is a growing demand for low-glycemic index (GI) foods. Research indicates that modified starches can slow down digestion and reduce the glycemic response, thereby contributing to better blood sugar management.[11,34,62,71] Resistant starch, a form of modified starch, is particularly effective in promoting gut health by acting as a prebiotic that supports the growth of beneficial gut bacteria.[53] Furthermore, the incorporation of modified starch in gluten-free products has been a game-changer for individuals with celiac disease or gluten intolerance, as it significantly improves the texture and sensory properties of such products.[27] Despite these advancements, long-term studies on the health impacts of consuming modified starch are remain limited, underscoring the need for further research in this area.[7]

The interactions between modified starches and other food components, such as proteins, fats, and non-starch polysaccharides, have a profound impact on food systems. These interactions affect the texture, stability, and nutritional profile of the final product. For instance, combining modified starch with proteins enhances the emulsification and gelation properties of food systems, making them suitable for applications in dairy and meat products.[21,51, 58] Similarly, the inclusion of modified starches in lipid-rich systems induces the formation of V-type crystalline structure and improve the overall the digestibility of waxy corn starch.[78] However, these benefits are highly dependent on the compatibility of starch with other ingredients, varies according to the modification technique used. Addressing these knowledge gaps is crucial for the development of standardized methods that ensure consistent quality in food production.

In summary, while considerable progress has been made, the field of starch modification continues to evolve, driven by the need to address challenges related to scalability, sustainability, and consumer health. Researchers increasingly prioritize the development of greener modification techniques that minimize environmental impact and energy consumption.[14,20,21,29] Additionally, there is a growing emphasis on understanding the long-term health implications of consuming modified starch, particularly in relation to gut microbiota and metabolic health. By addressing these challenges, future research can unlock the full potential of starch modification, ensuring that it continues to play a pivotal role in the creation of healthier, more sustainable food systems. The integration of advanced analytical techniques and interdisciplinary collaboration will be key to overcoming existing limitations and paving the way for innovative applications in the food industry. The advancements in starch modification techniques provide a foundation

 ISSN 2616-0684 (Print)
ISSN 2616-0692 (Electronic)

for developing starch-based products with tailored nutritional and functional properties, catering to diverse dietary and industrial needs.

Research Question

In a systematic literature review (SLR), research questions play a vital role by establishing the foundation and guiding the direction of the entire process. They help define the scope and focus of the review, guiding decisions on study inclusion or exclusion to maintain relevance and specificity. A well-crafted research question ensures that the literature search is thorough and systematic, capturing all relevant studies that address key aspects of the topic. This approach reduces bias and provides a complete overview of the available evidence.

Moreover, research questions help organize and categorize data from selected studies, creating a clear framework for analyzing findings and synthesizing results. This framework adds focus and clarity, minimizing ambiguity and keeping the review centered on specific issues, making the conclusions more practical and meaningful. Good research questions also enhance transparency and reproducibility, enabling other researchers to follow the same methodology, verify the findings, or expand the review to related areas.

Ultimately, research questions ensure that the review aligns with the overall objectives of the study, whether it is to identify gaps in the literature, evaluate the effectiveness of interventions, or explore trends in a specific field, making them the backbone of a rigorous, focused, and relevant systematic literature review. They align the review with the study's overall goals such as identifying knowledge gaps, evaluating interventions, or exploring trends—ensuring a focused and comprehensive analysis. This study emphasizes the importance of specifying research questions at the planning stage, as they drive the entire review process and methodology.[32] Using the PICo framework (Population, Interest, and Context) proposed by Lockwood *et al*.,[38] it is a mnemonic style used to formulate research questions, particularly in qualitative research. Here's what each component in PICo means:

1. Population (P): This refers to the group of participants of interest in the study. It specifies on the targets, such as a specific demographic, patient group, or community.

2. Interest (I): This represents the main focus or phenomenon of interest in the study. It could be a particular experience, behavior, intervention, or issue that the research aims to explore or understand.

3. Context (Co): This defines the setting, environment, or specific context in which the population and interest are situated. It might refer to geographical location, cultural or social settings, or any other relevant backdrop for the research.

The PICo framework aids in clearly and systematically structuring research questions by breaking down the key elements of the study into three components. This approach ensures a focused research direction and well-defined questions, facilitating the search for relevant literature or the design of the study. The study addresses the following three research questions:

1. What innovative techniques have been recently developed for starch modification.

2. How do specific starch modification methods influence the digestibility and functional properties of starch in food systems?

3. What are the key functional applications of modified starches in improving the quality and performance of food products?

Materials and Methods

In conducting systematic literature reviews, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, proposed by Page *et al.*)[43] is a widely recognized standard that ensures transparency, thoroughness, and consistency throughout the process. Adhering to the PRISMA guidelines, researchers can enhance the precision and rigor of their analysis, systematically identifying, screening, and including studies in their review. The method also emphasizes the importance of randomized studies, recognizing their capacity to minimize bias and provide robust evidence. This systematic review used two prominent databases, Scopus and ScienceDirect, due to their broad scope and reliability.

The PRISMA process is divided into four main stages: identification, screening, eligibility, and data abstraction as shown in Figure 1. During the identification stage, databases are searched to gather potentially relevant studies. The screening stage assesses these studies against predefined criteria to exclude those that are irrelevant or of low quality. In the eligibility stage, the remaining studies are carefully reviewed to ensure they meet the inclusion criteria. Finally, in the data abstraction stage, key information from the selected studies is extracted and synthesized, leading to the development of reliable conclusions. This systematic approach guarantees the review is conducted with rigor, producing credible results that can inform future research and practice.

Identification
This study followed key steps of the systematic review process to gather a comprehensive collection of relevant literature. The process began with selecting keywords, followed by identifying related terms using tools such as dictionaries, thesauri, encyclopaedias, and prior research. These terms were then consolidated to create search strings for querying the Scopus and ScienceDirect databases, as outlined in Table 1. This initial phase of the review yielded 411 publications relevant to the study topic from the two databases.

Screening
During the next screening phase of the systematic literature review (SLR) on starch modification, records were excluded based on specific criteria. These included eliminating non-English publications, those published prior to 2023, and materials categorized as conference proceedings, books, reviews, or in-press articles. Furthermore, studies outside the domains of Agricultural and Biological Sciences, Chemistry, Chemical Engineering, and Engineering were excluded, resulting in the removal of 350 records. Following this screening, 47 records from Scopus and 14 from ScienceDirect were retained, resulted in 61 papers. A duplicate check was then performed, leading to the removal of 7 duplicate papers.

Eligibility
In the eligibility phase, 54 articles were selected for review. During this stage, the titles and key content of all articles were thoroughly examined to ensure they met the inclusion criteria and aligned with the research objectives. As a result, 23 articles were excluded due to factors such as being out of scope, having irrelevant titles, containing abstracts not related to the study objectives, or not being accessible in full for empirical evidence. Consequently, 31 articles were retained for the next stage of the review.

Data Abstraction and Analysis
In this study, an integrative analysis approach was utilized as one of the assessment strategies to examine and synthesize a variety of research designs, with an emphasis on quantitative methods. The primary objective was to identify key topics and subtopics relevant to the research. The data collection phase marked the beginning of theme development. As shown in Table 2 and Table 3,-31 selected publications were meticulously reviewed, identifying assertions or content relevant to the study's focus. Then, significant studies related to starch modification technology were assessed, by analyzing both the methodologies used and the research findings.

Trop J Nat Prod Res, November 2025; 9(11): 5253 - 5266 ISSN 2616-0684 (Print)
ISSN 2616-0692 (Electronic)

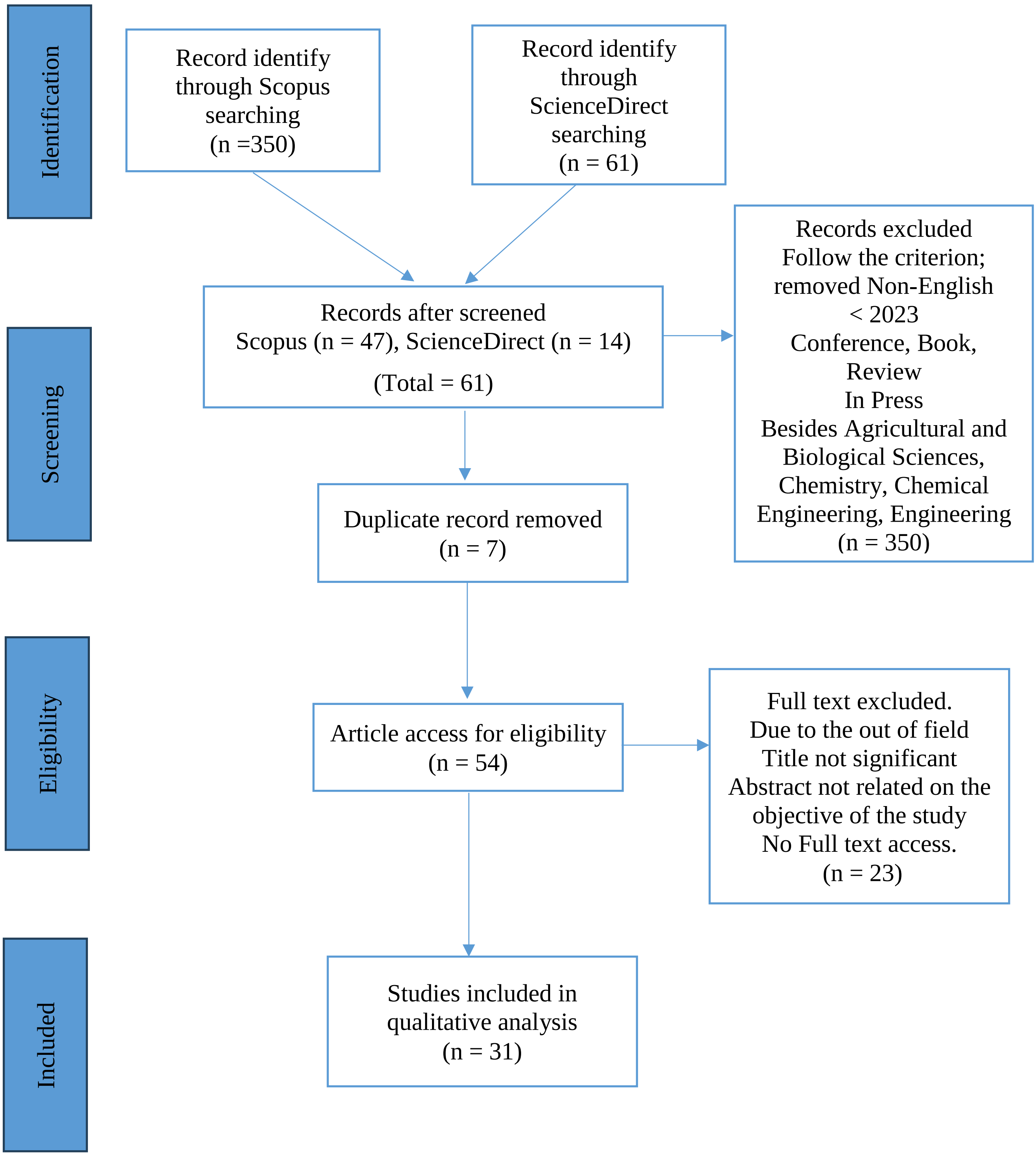

Figure 1: Flowchart illustrating the proposed search strategy for this study

Following this themes were developed based on the evidence gathered within the study's context. A log was kept throughout the data analysis process to record analyses, insights, uncertainties, or reflections related to data interpretation. Finally, the findings were compared to identify any inconsistencies in the theme development. In cases of disagreement, discussions were held to reach consensus.

Quality of Appraisal

According to the guidelines proposed by Kitchenham and Charters,[32] once the primary studies which refer to the original research articles, papers, or documents that are directly included in the systematic review after the initial selection process were selected, it was necessary to assess the quality of the research they present and quantitatively compare them.

 ISSN 2616-0684 (Print)
ISSN 2616-0692 (Electronic)

Table 1: The search string

Scopus	TITLE-ABS-KEY (technology AND starch AND (modify* OR treat*) AND (function* OR properties OR quality) AND (digest* OR resist*)) AND (LIMIT-TO (SUBJAREA , "AGRI") OR LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "CHEM") OR LIMIT-TO (SUBJAREA , "CENG")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR , 2024) OR LIMIT-TO (PUBYEAR , 2025)) AND (LIMIT-TO (PUBSTAGE , "final")) Date of Access: December 2024
Science Direct	technology AND starch AND (modify OR treat) AND (function OR properties OR quality) AND (digest OR resist) Date of Access: December 2024

These studies were considered the primary sources of evidence analyzed, assessed for quality, and compared quantitatively or qualitatively to answer the research questions defined for the review. In this study a quality assessment from Abouzahra *et al.*[2] was applied, which consists of six QAs for this SLR. The scoring procedure for evaluating each criterion involves three possible ratings: "Yes" (Y) with a score of 1 if the criterion was fully met, "Partly" (P) with a score of 0.5 if the criterion was somewhat met but contains some gaps or shortcomings, and "No" (N) with a score of 0 if the criterion was not met at all.

QA1. Is the purpose of the study clearly stated?

This criterion checks whether the study's objectives are clearly defined and articulated. A clear purpose helps set the direction and scope of the research.

QA2. Is the interest and the usefulness of the work clearly presented?

This criterion evaluates whether the study's significance and potential contributions are well-explained. It measures the relevance and impact of the research.

QA3. Is the study methodology clearly established?

This assesses whether the research methodology is well-defined and appropriate for achieving the study's objectives. Clarity in methodology is crucial for the study's validity and reproducibility.

QA4. Are the concepts of the approach clearly defined?

This criterion looks at whether the theoretical framework and key concepts are clearly articulated. Clear definitions are essential for understanding the study's approach.

QA5. Is the work compared and measured with other similar work?

This evaluates whether the study has been benchmarked against existing research. Comparing with other studies helps position the work within the broader academic context and highlights its contributions.

QA6. Are the limitations of the work clearly mentioned?

This evaluates whether the study explicitly state the limitation to acknowledge any constraints in methodology, sample size, scope, or data interpretation that may affect the validity or generalizability of the findings. Clearly discussing these limitations allows readers to critically assess the study's reliability and identify areas for future research improvement.

The tables outline a quality assessment (QA) process used to evaluate a study based on specific criteria.

For a study to be accepted for the next process, the total mark, derived from summing the scores from all three experts, must exceed 3.0. This threshold ensures that only studies meeting a certain quality standard proceed further.

Table 2: The selection criterion in searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Time line	2023 – 2025	< 2023
Literature type	Journal (Article)	Conference, Book, Review
Publication Stage	Final	In Press
Subject Area	Agricultural and Biological Sciences, Chemistry, Chemical Engineering, Engineering	Besides Agricultural and Biological Sciences, Chemistry, Chemical Engineering, Engineering

Trop J Nat Prod Res, November 2025; 9(11): 5253 - 5266 ISSN 2616-0684 (Print)
ISSN 2616-0692 (Electronic)

Results and Discussion

Table 4 shows the result of assessment performance for selected primary studies in which:

- **Highest Score**: Four papers achieved 100% in the quality assessment. The papers by Liang *et al.*,[37] Sun *et al.*,[62] Saeva *et al.*[52]and Galvão *et al.*[18] achieved the highest score due to clear articulation of purpose, usefulness, methodology, defined concepts, comparison with other work, and mention of limitations.
- **Lowest Score**: The papers by Almeida *et al.*[4] and Araoye *et al.*[6] scored the lowest (75 %), as they partly met the criteria for approach and comparison with other work, and did not mention limitations.

The quality assessment of the 31 selected articles revealed generally high standards of research, with most studies demonstrating clear objectives, robust methodologies, and significant contributions to the field. Nearly all articles clearly stated the purpose of their research, linking it to practical applications or addressing current challenges in food science and starch modification.

Table 3: Details of primary studies database

No	Study	Journal	Scopus	Science direct
1	He *et al*. (2024)[25]	Food Chemistry: X	/	
2	Santos *et al*. (2023)[54]	Journal of Food Measurement and Characterization	/	
3	Fashi *et al*. (2024)[14]	Food Chemistry	/	
4	Liang *et al*. (2023)[37]	Food and Bioprocess Technology	/	
5	Sun *et al*. (2023)[62]	Journal of Food Quality	/	
6	Ye *et al*. (2025)[76]	Food Chemistry	/	
7	Song *et al*. (2024)[61]	Food and Bioprocess Technology	/	
8	Thongkong *et al.* (2024)[64]	Processes	/	
9	Saeva *et al*. (2023)[52]	International Journal of Food Science and Technology	/	
10	Mowafy and Liu (2024)[39]	Food and Bioprocess Technology	/	
11	Galvão *et al*. (2024)[18]	Foods	/	
12	Wang *et al*. (2023)[67]	Food Biophysics	/	
13	Kumar *et al*. (2024)[33]	Journal of Plant Biochemistry and Biotechnology	/	
14	He *et al*. (2024)[24]	Food Chemistry	/	/
15	Xiao *et al*. (2023)[73]	Food Chemistry		
16	Chavez-Villegas *et al.* (2024)[8]	Food Bioscience	/	/
17	Yao *et al*. (2023)[75]	Processes		/
18	Nunes *et al*. (2024)[42]	International Journal of Food Science and Technology		/

ISSN 2616-0684 (Print)
ISSN 2616-0692 (Electronic)

19	Zhang *et al*. (2025)[80]	Food Research International	/	/
20	Vidhyalakshmi and Meera (2023)[66]	Journal of Food Measurement and Characterization		/
21	Fashi *et al*. (2023)[15]	Starch/Staerke		/
22	Ge *et al*. (2024)[19]	Food Research International		/
23	Najib *et al*. (2023)[41]	Food Chemistry Advances	/	/
24	Fashi *et al*. (2024)[14]	Food Hydrocolloids		/
25	Almeida *et al*. (2025)[4]	Food Chemistry	/	/
26	Sartori *et al*. (2023)[55]	Innovative Food Science and Emerging Technologies	/	/
27	Gong *et al*. (2023)[20]	LWT	/	/
28	Araoye *et al*. (2024)[6]	Food and Humanity		/
29	Zhang *et al*. (2023)[77]	Food Chemistry		/
30	Gu *et al*. (2024)[22]	Carbohydrate Polymers		/
32	Araoye *et al*., (2024)[6]	Food and Humanity		/

Footnote here: "/" indicated the study was found in selected database

This clarity of purpose (QA1) and the relevance of the findings (QA2) were consistent strengths across the body of work, emphasizing the alignment of these studies with both academic and industry needs. The methodologies employed (QA3) were largely well-established, involving advanced analytical techniques such as scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), and in vitro digestion assays. These methods allowed for precise analysis of starch structure, physicochemical properties, and digestibility under various modification treatments.

The approaches used in the studies were generally well-defined, with clear conceptual frameworks guiding the experiments (QA4). This reflects a thorough understanding among researchers' of the scientific principles underlying starch modification and its implications for food functionality. However, the comparative analysis with similar works (QA5) showed some variability. While most studies included relevant comparisons to highlight the novelty and efficacy of their findings, the depth of these comparisons varied. Some articles lacked detailed benchmarking against alternative methods, which could have strengthened the validation of their results. Furthermore, the acknowledgment of limitations (QA6) was often insufficient or missing, with many studies briefly mentioning constraints or entirely omitting discussions on the boundaries of their research. This lack of transparency can affect the reproducibility of results and the practical application of findings. The majority of the reviewed articles achieved scores between 75–100%, reflecting good to excellent quality. Studies with higher scores stood out for applying solid research methods and offering clear, practical insights, whereas those with lower scores often lacked depth in comparative analysis and discussions on study limitations. Key research areas focused on improving starch functionality through eco-friendly technologies, developing resistant starch for health benefits, and promoting the sustainable use of agricultural resources. These findings highlight encouraging progress in creating innovative food ingredients like modified flours and starch-lipid complexes, catering to the growing demand for healthier and more sustainable food options.

In summary, this collection of research has greatly contributed to the understanding of starch modification and its role in food science. Nonetheless, there is still room to enhance comparative analysis and openly discuss study limitations. Moving forward, future studies should prioritise transparency and interdisciplinary collaboration to maximise the relevance and impact of their findings. By addressing these gaps, subsequent studies can build on the solid foundation established by this work, driving innovation in food science and technology.

Based on the quality assessment, articles were categorized into three main themes which highlights the diverse methodologies, structural insights, and functional advancements across various studies as shown in Table 5.

Advances in Starch Modification Techniques

Starch modification has become a pivotal area in food science due to its potential to enhance functional properties and broaden applications.

ISSN 2616-0684 (Print)
ISSN 2616-0692 (Electronic)

Table 4: Quality assessment of selected primary studies

Study	QA1	QA2	QA3	QA4	QA5	QA6	Total Mark	%
1	Y	Y	Y	Y	P	P	5.5	91.67%
2	Y	Y	Y	P	Y	P	5.5	91.67%
3	Y	Y	Y	Y	P	P	5.5	91.67%
4	Y	Y	Y	Y	Y	P	6	100%
5	Y	Y	Y	Y	Y	P	6	100%
6	Y	Y	P	Y	P	Y	5.5	91.67%
7	Y	Y	Y	P	Y	P	5.5	91.67%
8	Y	Y	Y	Y	Y	Y	6	100%
9	Y	Y	Y	Y	P	P	5.5	91.67%
10	Y	Y	Y	Y	Y	Y	6	100%
11	Y	Y	Y	P	P	P	5.5	91.67%
12	Y	Y	Y	Y	Y	P	5.5	91.67%
13	Y	Y	Y	Y	Y	P	5.5	91.67%
14	Y	Y	Y	Y	P	P	5.0	83.33%
15	Y	Y	Y	Y	P	P	5.0	83.33%
16	Y	Y	Y	Y	P	Y	5.5	91.67%
17	Y	Y	Y	Y	P	P	5.0	83.33%
18	Y	Y	Y	Y	P	P	5.0	83.33%
19	Y	Y	Y	Y	P	P	5.0	83.33%
20	Y	Y	Y	Y	P	P	5.0	83.33%
21	Y	Y	Y	Y	P	P	5.0	83.33%
22	Y	Y	Y	Y	P	P	5.0	83.33%
23	Y	Y	Y	Y	P	P	5.0	83.33%
24	Y	Y	Y	Y	P	P	4.5	75%
25	Y	Y	Y	Y	Y	P	5	83.33%
26	Y	Y	Y	Y	P	Y	5.5	91.67%
27	Y	Y	Y	Y	P	Y	5.5	91.6
28	Y	Y	P	Y	P	P	4.5	75%
29	Y	Y	Y	Y	Y	P	5.0	83.33%
30	Y	Y	Y	Y	P	Y	5.0	83.33%
31	Y	Y	Y	Y	P	P	4.5	75%

*Y: Yes, P: Partly

Various innovative methods have been adopted, including physical, chemical, enzymatic, and combined treatments, to improve structural characteristics, digestibility, and overall functionality. Recent studies reveal the efficacy of these approaches in tailoring starch properties for specific applications.

Studies highlight that those structural modifications significantly influence functional properties. For instance, He *et al.*[24] demonstrated that ball milling, extrusion puffing, and enzymatic treatments enhanced hydration properties, solubility, and resistant starch (RS) content in kudzu starch. These methods increased solubility up to 80% and RS content to 86.87%, suggesting their suitability for instant food applications. Similarly, Fashi *et al.*[13a] observed that dielectric barrier discharge plasma combined with dry heat enhanced esterification efficiency and gelatinization enthalpy in corn starch, facilitating its use in low-calorie food formulations. Liang *et al.*[37] confirmed that plasma and E-beam pre-treatments disrupted crystallinity and improved solubility, highlighting the dual modification's ability to achieve superior RS content compared to the single method.

Non-thermal techniques such as pulsed electric field (PEF) and ultrasound-assisted enzymatic hydrolysis have been pivotal in starch modification.[54] reported that PEF treatments improved solubility, antioxidant activity, and reduced drying time for mango peels, emphasizing the sustainability of non-thermal methods. Likewise, Sun *et al*.[62] found that ultrasound-assisted α-amylase degradation significantly increased RS yield in arrowhead starch while maintaining structural stability. These findings align with He *et al*.[24] who noted improved swelling power and translucency in cornstarch through ultrasonic pre-treatments.

 ISSN 2616-0684 (Print)
ISSN 2616-0692 (Electronic)

The synergy of dual modification techniques is beneficial for optimizing starch properties. Fashi *et al.*,[14] highlighted the effectiveness of repeated freeze-thaw cycles and microwave-assisted esterification in enhancing RS content and thermal stability in corn starch. Similarly, Zhang *et al.*[80] demonstrated that dual hydrothermal treatments improved crystallinity and RS content in wheat starch while maintaining structural integrity. Such approaches demonstrate the value of combining treatments in achieving functional versatility.

Environmentally friendly methods like dry heat and ultrasonication offer practical benefits. Vidhyalakshmi and Meera [66] showed that these treatments enhanced RS content and reduced the glycemic index in pearl millet flour, supporting its inclusion in low-GI food products. Wang *et al.*[67] noted that electron beam irradiation not only increased RS content in wheat starch but also reduced swelling power, signifying its application in high-starch foods. These insights affirm the potential of green technologies in sustainable starch processing.

The reviewed studies collectively establish that innovative modification techniques, including physical, enzymatic, and non-thermal methods, significantly improve the structural and functional properties of starch. Dual modification approaches exhibit synergistic effects, optimizing digestibility and functionality. These advancements contribute to the development of tailored starch-based products, to address diverse consumer and industrial needs while also promoting sustainability.

Starch Digestibility and Functional Properties

Recent advancements in starch modification, particularly concerning digestibility and functional properties, have garnered significant research attention. A review of recent findings highlights several notable methodologies, findings, and their implications for food systems.

Insights into starch digestibility

Studies have revealed diverse approaches to modulating starch digestibility through thermal and non-thermal treatments. For instance, Ye *et al.*[76]demonstrated that radio frequency explosion puffing of yam flour significantly alters its microstructure, enhancing enzymatic digestibility. This finding aligns with observations by Najib *et al.*[41] who investigated lentil seeds and found that microwave-assisted techniques effectively disrupt starch granule structures, improving accessibility to digestive enzymes. Similarly, Gu *et al.*[22] noted that heat-moisture treatment on high-amylose maize enhances enzymatic resistance while simultaneously improving thermal stability. The application of pulsed electric fields, as reported by Thongkong *et al.*[63] also showed promise for improving starch digestion kinetics in rice. Their findings emphasized that this method modifies the physicochemical properties of starch, creating a balance between digestibility and functional quality. These outcomes are complemented by Saeva *et al.*[51] who highlighted that understanding the structural interplay in white rice is key to optimizing starch digestibility without compromising the grain's integrity.

Structural and Physicochemical Transformations

Cooking methods significantly influence starch structure and its subsequent properties. Yao *et al.*[75] compared the effects of various cooking techniques on rice and reported that methods resulting in lower glycemic responses were associated with specific structural transformations. Likewise, Mowafy and Liu[40] showed that conventional and novel steam blanching methods on potatoes modify starch crystallinity thereby enhancing digestibility and functional versatility. Extrusion processing, as explored by Ge *et al.*[19] in highland barley flour, was shown to effectively disrupt starch molecules, resulting in enhanced solubility and gelation properties. This aligns with Shah *et al.*[60] who indicated that ultrasound treatments during the soaking process of parboiled rice led to improve in vitro digestibility and changes instarch's crystalline structure.

Functional Enhancements in Modified Starches

Modifications aimed at functional applications have also been explored extensively. Gong *et al.* [20] investigated green composite modifications on rice flour, demonstrating improvements in functional properties such as water retention and swelling, which concurrently enhanced digestibility. Additionally, Kumar *et al.*[33] highlighted that hydrothermal infrared treatments effectively extend the shelf life of pearl millet flour while retaining its nutrient density and functional quality. This approach aligns with the findings of Thongkong *et al.*[64] who emphasized the functional benefits of rapid cooking technologies that preserve nutritional profiles. The convergence of methodologies indicates a growing focus on integrating digestibility enhancements with functional benefits. The findings by Najib *et al.*[41] and Gu *et al.*[22] exemplify efforts to develop starches that are both enzymatically accessible and thermally stable, catering to diverse food processing needs. In summary, the body of research emphasized the pivotal role of innovative processing methods in modulating starch digestibility and functional properties. Techniques such as heat-moisture treatment, extrusion, ultrasound application, and pulsed electric fields have emerged as transformative approaches. Collectively, these findings contribute to the development of starch-based ingredients with enhanced nutritional and functional profiles.

Functional Applications of Modified Starches in Food Systems

Advances in nutritional and textural enhancement of food products

Recent innovations in starch modification have demonstrated significant potential for improving the nutritional and sensory qualities of food products. For example, Song *et al.*[61] revealed that the application of magnetic fields during the preparation of steamed bread enriched with potato pulp led to enhancements in phenolic content, antioxidant capacity, and cross-linking structure, as well as improved aroma and textural attributes. Similarly, Nunes *et al.*[42] reported that gluten-free cakes prepared with heat-moisture-treated rice starch and avocado oil exhibited superior textural softness, better bioactive compound retention, and reduced glycemic index compared to formulations with native starch. These findings underscore the role of innovative starch modification techniques in developing health-oriented food products with desirable sensory and functional characteristics.

Improvements in digestibility and functional properties

Modifications to starch structure directly impact digestibility and the formation of resistant starch fractions, which are critical for developing functional foods. Chavez-Villegas *et al.*[8] utilized plasma-activated water to modify starch, reporting enhanced resistant starch content, particularly in high amylose starch, Xiao *et al.* [73] found that ultrasound pretreatment of pea starch significantly improved its complexing capacity with lipids, yielding enhanced resistant starch content and thermal stability. Similarly, Zhang *et al.* [78] demonstrated that enzymatic modification of waxy corn starch increased the formation of V-type starch-lipid complexes, which improved thermal stability and shifted the digestibility profiles toward slowly digestible fractions. These studies collectively highlight the potential of advanced physical and enzymatic treatments in tailoring starch digestibility for functional applications.

Enhancement of technological and physicochemical characteristics

The application of novel starch modification techniques has also been shown to enhance the technological and physicochemical properties of food systems. Galvão *et al.*[18] developed edible coatings using yam starch and pineapple peel flour to improve the shelf life of acerola fruits. Their study demonstrated effective weight loss reduction, color preservation, and delayed degradation of soluble solids during storage. Fashi *et al.*[12] observed that a ternary treatment combining ultrasound, stirring, and lactic acid significantly altered the structural and physicochemical properties of corn starch, including increased water holding capacity, swelling power, and resistant starch fractions. Araoye *et al.*[6] confirmed that acetylation improved the functional properties of lima bean powder, including enhanced paste clarity, decreased retrogradation tendencies, and improved thermal stability. Collectively, these findings illustrate the technological versatility of modified starches in enhancing product stability and functionality.

ISSN 2616-0684 (Print)
ISSN 2616-0692 (Electronic)

Table 5: Summary of research articles categorized under three major themes: Innovations in starch modification techniques, starch digestibility and functional properties, and functional applications of modified starches in food systems

Theme	Articles
Innovations in Starch Modification Techniques	1. Structural-functional analysis of modified kudzu starch as a novel instant powder: Role of modified technology 2. Effect of pulse electric field (PEF) intensity combined with drying temperature on mass transfer, functional properties, and in vitro digestibility of dehydrated mango peels 3. Dielectric barrier discharge plasma pre-treatment to facilitate the acetylation process of corn starch under heating/cooling cycles 4. Comparison Study of DBD Plasma Combined with E-Beam Pre- and Post-treatment on the Structural-Property Improvement of Chinese Yam Starch. 5. Characterization of Arrowhead-Derived Type 3 Resistant Starch Prepared by Ultrasound-Assisted α-Amylase Degradation. 12. Effect of 10 MeV Electron Beam Irradiation on the Structure and Functional Properties of Wheat Starch 14. Effects of ultrasonic and chemical dual modification treatments on the structural, and properties of cornstarch 16. In situ starch and water modification using atmospheric plasma: Structure, functionality and in vitro digestibility 19. Insights into the regulation mechanisms of dual hydrothermal treatment on the structure and digestive characteristics of A- and B-type wheat starch granules 20. Dry heat and ultrasonication treatment of pearl millet flour: effect on thermal, structural, and in-vitro digestibility properties of starch 25. Green modification of corn starch through repeated freeze-thaw cycles (RFTC), microwave assisted solid state acetic acid esterification (MSAE), and by dual RFTC/MSAE treatment 26. Synergistic effect of ozone treatment with α-amylase on the modification of microstructure and paste properties of japonica rice starch
Starch Digestibility and Functional Properties	6. Effect of endogenous proteins and lipids on yam flour during radio frequency explosion puffing: Characterization, microstructure, function, and in vitro digestibility 8. Pulsed Electric Field for Quick-Cooking Rice: Impacts on Cooking Quality, Physicochemical Properties, and In Vitro Digestion Kinetics 9. Understanding starch digestibility of rice: a study in white rice 10. Novel and Conventional Steam Blanching Impacts on Potato Starch Digestibility and Physicochemical Properties 13. Hydrothermal infra-red (HT-IR): the most effective technology for enhancing the shelf-life of pearl millet flour without compromising with the nutrient density and flour quality 17. Effects of Different Cooking Methods on Glycemic Index, Physicochemical Indexes, and Digestive Characteristics of Two Kinds of Rice 23. Exploring the relationship between starch structure and physicochemical properties: The impact of extrusion on highland barley flour 24. Modification in starch structure of soaked and germinated lentil seeds under various thermal processing methods, including conventional, microwave, and microwave-assisted techniques 28. New insights into influence of green composite modification on the structure, digestive, and physicochemical properties of rice flour 31. Heat-moisture treatment of freshly harvested high-amylose maize kernels improves its starch thermal stability and enzymatic resistance 32. Insights into the structural characteristics and in vitro starch digestibility on parboiled rice as affected by ultrasound treatment in soaking process
Functional Applications of Modified Starches in Food Systems	7. Influence of Magnetic Field Intensity on the Quality Characteristics of Steamed Bread Enriched with Potato Pulp 11. Development of Edible Coatings Based on Pineapple Peel (*Ananas Comosus* L.) and Yam Starch (*Dioscorea alata*) for Application in Acerola (*Malpighia emarginata* DC) 18. Avocado oil used to modify rice starch and prepare gluten-free cakes: physical–chemical, microbiological, sensory, and nutritional evaluations 21. Study on Structural and Physicochemical Properties of Modified Corn Starch: Comparison of Ultrasound, Stirring, and Lactic Acid Treatments 22. Techno-functional and nutritional variations of *Cardaba* banana flour as influenced by different modification techniques 27. Anthocyanin bioaccessibility and anti-inflammatory activity of a grape-based 3D printed food for dysphagia 29. Effect of acetylation on the functional characteristics of lima bean (*Phaseolus lunatus*) 30. Fabrication and characterization of starch-lipid complexes using chain-elongated waxy corn starches as substrates

Bioactive compound preservation and functional applications in special diets

Starch modifications also enable the incorporation and stabilization of bioactive compounds in food matrices. Sartori *et al.*[55] developed 3D-printed hydrogels using modified cassava starch for dysphagia diets, reporting increased anthocyanin bioaccessibility and anti-inflammatory activity. Similarly, Nunes *et al.*[42] highlighted the role of modified rice starch in retaining phenolic compounds in gluten-free cakes, enhancing their nutritional profile. These applications demonstrate how starch modification can create specialized food products targeting specific health needs while maintaining bioactive compound efficacy. The reviewed studies collectively demonstrate that starch modification is a versatile tool for enhancing the functional, nutritional, and technological properties of food systems. Techniques such as magnetic field application, ultrasound pretreatment, enzymatic modification, and chemical treatments like acetylation provide pathways to develop innovative food products with tailored characteristics. These advancements pave the way for broader applications in health-focused and specialized food formulations.

Conclusion

The modification of starch has emerged as a critical focus in food science, driven by its potential to improve functional properties and expand applications across various sectors. Advanced methods, including physical, chemical, enzymatic, and dual treatments, have been extensively researched because of their capacity to enhance starch's structural characteristics, digestibility, and overall utility of starch. These techniques have proven effective in tailoring starch for specific functional and nutritional applications. Structural modifications are shown to significantly influence the functional properties of starch. Techniques such as ball milling, extrusion puffing, and enzymatic treatments have demonstrated substantial improvements in hydration properties, solubility, and resistant starch (RS) content, making them suitable for instant and low-calorie food applications. Similarly, innovative approaches like dielectric barrier discharge plasma and dry heat treatments have been successful in effectively enhanced esterification efficiency and thermal stability, making them suitable in a variety of food formulations. Non-thermal methods, including pulsed electric field (PEF) and ultrasound-assisted enzymatic hydrolysis, have gained attention for their efficiency and sustainability. These methods have been effective in improving solubility, antioxidant activity, and resistant starch yield while reducing processing time and maintaining structural stability. The integration of these techniques further underscores their relevance in modern starch processing. Dual modification strategies, such as the combination of hydrothermal treatments or microwave-assisted esterification with repeated freeze-thaw cycles, have been particularly successful in optimizing starch functionality. These approaches demonstrate consistent improvement in resistant starch content, crystallinity, and thermal stability, showing their versatility for achieving targeted functional outcomes. Environmentally friendly techniques, including dry heat and ultrasonication, have also shown significant promise. These methods have enhanced resistant starch content and lowered the glycemic index of starch-based products, aligning with the demand for sustainable and health-conscious food processing technologies. Furthermore, advancements such as electron beam irradiation have expanded the functional applications of starch by improving resistant starch content and altering swelling properties. Starch modification has also facilitated the stabilization and incorporation of bioactive compounds in food matrices, enabling the development of specialized dietary products. Examples include 3D-printed hydrogels for dysphagia diets and gluten-free formulations with enriched phenolic content. These innovations demonstrate the potential of modified starches to meet specific dietary needs while preserving bioactive efficacy. Overall, the diverse methods and innovative combinations explored in starch modification highlight their potential to meet evolving industrial and consumer needs. The integration of sustainable and efficient techniques reflects a growing emphasis on health, functionality, and environmental considerations in starch-based food processing. Therefore, future research should focus on integrating sustainable modification techniques with advanced food technologies to develop starch-based ingredients that simultaneously address health, functionality, and environmental sustainability.

Conflict of Interest

The authors declare no conflict of interest.

Author's Declaration

The authors hereby declare that the work presented in this article is original and that any liability for claims relating to the content of this article will be borne by them.

Acknowledgements

This research was made possible by funding from Universiti Tun Hussein Onn Malaysia (UTHM) through GPPS (Vot Q674). Communication of this research is made possible through monetary assistance by Universiti Tun Hussein Onn Malaysia and the UTHM Publisher's Office via Publication Fund E15216.

References

1. Abdrabuo MM, Hefnawy TH, Al-Khatib AY, El-Maghraby LM. Effect of Cross-Linking on Some Properties of Corn Starch. Zagazig J. Agric. Res. 2020; 47(5):1189-1199. https://doi.org/10.21608/zjar.2020.247960
2. Abouzahra A, Sabraoui A, Afdel K. Model composition in Model Driven Engineering: A systematic literature review. Information and Software Technology. 2020; 125:106316. https://doi.org/10.1016/j.infsof.2020.106316
3. Adewumi FD, Lajide L, Adetuyi AO, Ayodele O. Functional properties of three native starches and their modified derivatives. Potravin. Slovak J. Food Sci. 2020; 14:682-691. https://doi.org/10.5219/1232
4. Almeida RL, Santos NC, Monteiro SS, Monteiro SS, Feitoza JV, de Almeida Mota MM, da Silva Eduardo R, Sampaio PM, da Costa GA, de Bittencourt Pasquali MA, de Almeida Silva R. Synergistic effect of ozone treatment with α-amylase on the modification of microstructure and paste properties of japonica rice starch. Food Chem. 2025; 465:142145. https://doi.org/10.1016/j.foodchem.2024.142145
5. Amarnath MS, Muhammed A, Antony AK, Malini B, Sunil CK. White finger millet starch: Physical modification (annealing and ultrasound), and its impact on physicochemical, functional, thermal and structural properties. Food and Humanity. 2023; 1:599-606. https://doi.org/10.1016/j.foohum.2023.07.010
6. Araoye KT, Akinola SA, Oyelade AM, Ogagar S, Oyewale MB, Ogunbusola EM, Sanni TA, Oludahunsi OF. Effect of acetylation on the functional characteristics of lima bean (*Phaseolus lunatus*). Food and Humanity. 2024; 2:100237. https://doi.org/10.1016/j.foohum.2024.100237
7. Bhatt P, Kumar V, Goel R, Sharma SK, Kaushik S, Sharma S, Shrivastava A, Tesema M. Structural Modifications and Strategies for Native Starch for Applications in Advanced Drug Delivery. Biomed Res Int. 2022; 1:2188940. https://doi.org/10.1155/2022/2188940
8. Chavez-Villegas M, Flores-Silva PC, Hernandez-Hernandez E, Bello-Pérez LA, Ceniceros-Reyes M, Garcia-Hernandez A, Sifuentes-Nieves I. In situ starch and water modification using atmospheric plasma: Structure, functionality and in vitro digestibility. Food Biosci. 2024; 61:104761. https://doi.org/10.1016/j.fbio.2024.104761
9. Christensen SJ, Madsen MS, Zinck SS, Hedberg C, Sørensen OB, Svensson B, Meyer AS. Enzymatic potato starch modification and structure-function analysis of six diverse GH77 4-alpha-glucanotransferases. Int. J. Biol. Macromol. 2023; 224:105-114.

https://doi.org/10.1016/j.ijbiomac.2022.10.107

10. Chung C, Degner B, McClements DJ. Rheology and microstructure of bimodal particulate dispersions: Model for foods containing fat droplets and starch granules. Food Res Int. 2012; 48(2):641-649. https://doi.org/10.1016/j.foodres.2012.06.011
11. Faridah DN, Silitonga RF, Indrasti D, Afandi FA, Jayanegara A, Anugerah MP. Verification of autoclaving-cooling treatment to increase the resistant starch contents in food starches based on meta-analysis result. Front. Nutr. 2022; 9:904700. https://doi.org/10.3389/fnut.2022.904700
12. Fashi A, Delavar AF, Zamani A, Noshiranzadeh N. Lactic acid esterification of maize starch in solid state: assistant effect of pullulanase modification on digestibility and physicochemical properties. J Cereal Sci. 2023; 109:103617. https://doi.org/10.1016/j.jcs.2022.103617
13. Fashi A, Delavar AF, Zamani A, Noshiranzadeh N, Ebadipur H, Ebadipur H, Khanban F. Dielectric barrier discharge plasma pre-treatment to facilitate the acetylation process of corn starch under heating/cooling cycles. Food Chem. 2024; 453:139711. https://doi.org/10.1016/j.foodchem.2024.139711
14. Fashi A, Delavar AF, Zamani A, Noshiranzadeh N, Ebadipur H, Ebadipur H, Khanban F. Green modification of corn starch through repeated freeze-thaw cycles (RFTC), microwave assisted solid state acetic acid esterification (MSAE), and by dual RFTC/MSAE treatment. Food Hydrocoll. 2024; 146:109303. https://doi.org/10.1016/j.foodhyd.2023.109303
15. Fashi A, Delavar AF, Zamani A, Noshiranzadeh N, Zahraei H. Study on structural and physicochemical properties of modified corn starch: Comparison of ultrasound, stirring, and lactic acid treatments. Starch-Stärke. 2023; 75(3-4):2200109. https://doi.org/10.1002/star.202200109
16. Fashi A, Delavar AF, Zamani A, Noshiranzadeh N. Solid state malic acid esterification on fungal α-amylase treated corn starch: design of a green dual treatment. Food Chem. 2023; 410:135439. https://doi.org/10.1016/j.foodchem.2023.135439
17. Fonseca LM, El Halal SL, Dias AR, da Rosa Zavareze E. Physical modification of starch by heat-moisture treatment and annealing and their applications: A review. Carbohydr. Polym. 2021; 274:118665. https://doi.org/10.1016/j.carbpol.2021.118665
18. Galvão MB, Stamford TC, de Melo FA, de Lima GS, de Oliveira CE, de Oliveira IL, Bidô RD, Pintado MM, de Oliveira ME, Stamford TL. Development of edible coatings based on pineapple peel (*Ananas comosus* L.) and yam starch (*Dioscorea alata*) for application in acerola (*Malpighia emarginata* DC). Foods. 2024; 13(18):2873. https://doi.org/10.3390/foods13182873
19. Ge F, Sun Y, Yang C, Cheng W, Wang Z, Xia X, Wu D, Tang X. Exploring the relationship between starch structure and physicochemical properties: The impact of extrusion on highland barley flour. Food Res Int. 2024; 183:114226. https://doi.org/10.1016/j.foodres.2024.114226
20. Gong X, Li J, Liu Z, Xu X, Wang A, Nie M, Lin R, Tian Y, Zhang X, Wang L, Liu L. New insights into influence of green composite modification on the structure, digestive, and physicochemical properties of rice flour. LWT. 2023; 189:115491. https://doi.org/10.1016/j.lwt.2023.115491
21. Gong Y, Xiao S, Yao Z, Deng H, Chen X, Yang T. Factors and modification techniques enhancing starch gel structure and their applications in foods: A review. Food Chem: X. 2024; 24:102045. https://doi.org/10.1016/j.fochx.2024.102045
22. Gu Z, Cheng G, Sha X, Wu H, Wang X, Zhao R, Huang Q, Feng Y, Tang J, Jiang H. Heat-moisture treatment of freshly harvested high-amylose maize kernels improves its starch thermal stability and enzymatic resistance. Carbohydr. Polym. 2024; 340:122303. https://doi.org/10.1016/j.carbpol.2024.122303
23. Guo Y, Qiao D, Zhao S, Zhang B, Xie F. Starch-based materials encapsulating food ingredients: Recent advances in fabrication methods and applications. Carbohydr. Polym. 2021; 270:118358. https://doi.org/10.1016/j.carbpol.2021.118358
24. He, M., Wu, X., Gao, T., Chen, L., Teng, F., & Li, Y. (2024). Effects of ultrasonic and chemical dual modification treatments on the structural, and properties of cornstarch. *Food chemistry*, *451*, 139221. https://doi.org/10.1016/j.foodchem.2024.139221
25. He R, Du C, Li S, Guo L, Wang K, Yang L. Structural-functional analysis of modified kudzu starch as a novel instant powder: Role of modified technology. Food Chem: X. 2024; 24:101912. https://doi.org/10.1016/j.fochx.2024.101912
26. Himat AS, Gautam S, Garcia JP, Vidrio-Sahagún AX, Liu Z, Bressler D, Vasanthan T. Starch-based novel ingredients for low glycemic food formulation. Bioact Carbohydrates Diet Fibre. 2021; 26:100275. https://doi.org/10.1016/j.bcdf.2021.100275
27. Hussain SZ, Beigh MA, Qadri T, Naseer B, Zargar I. Development of low glycemic index muffins using water chestnut and barley flour. J Food Process Preserv. 2019; 43(8):e14049. https://doi.org/10.1111/jfpp.14049
28. Iftikhar SA, Dutta H. Status of polymorphism, physicochemical properties and in vitro digestibility of dual retrogradation-annealing modified rice starches. Int J Biol Macromol. 2019; 132:330-339. https://doi.org/10.1016/j.ijbiomac.2019.03.206
29. Ilamaran M, Sarojinibharathi R, Selvi J. Development of technology for modified starch incorporated grains and pulse blended bakery and pasta products. J. Appl. & Nat. Sci. 2021; 13(SI):179. https://doi.org/10.31018/jans.v13iSI.2825
30. Jeevarathinam G, Ramniwas S, Singh P, Rustagi S, Asdaq SM, Pandiselvam R. Macromolecular, thermal, and nonthermal technologies for reduction of glycemic index in food-A review. Food Chem. 2024; 445:138742. https://doi.org/10.1016/j.foodchem.2024.138742
31. Chiravi K, Khan MA, Wadikar DD, Mahesh C, Semwal AD. Starch retrogradation: Role of food ingredients and extrinsic factors. Food Sci Eng. 2023: 204-215. https://doi.org/10.37256/fse.4220232939
32. Kitchenham B, Charters S. Guidelines for performing systematic literature reviews in software engineering. EBSE Technical Report, Keele University and Department of Computer Science University of Durham. 2007; 2.
33. Kumar RR, Singh N, Goswami S, Vinutha T, Singh SP, Mishra GP, Kumar A, Jha GK, Satyavathi CT, Praveen S, Tyagi A. Hydrothermal infra-red (HT-IR): the most effective technology for enhancing the shelf-life of pearl millet flour without compromising with the nutrient density and flour quality. J. Plant Biochem. Biotechnol. 2024; 33(3):326-340. https://doi.org/10.1007/s13562-024-00893-1
34. Lee CS, Chung HJ. Enhancing resistant starch content of high amylose rice starch through heat–moisture treatment for industrial application. Molecules. 2022; 27(19):6375. https://doi.org/10.3390/molecules27196375
35. Li B, Zhang Y, Luo W, Liu J, Huang C. Effect of new type extrusion modification technology on supramolecular structure and in vitro glycemic release characteristics of

starches with various estimated glycemic indices. Front. Nutr. 2022; 9:985929. https://doi.org/10.3389/fnut.2022.985929
36. Li H, Gui Y, Li J, Zhu Y, Cui B, Guo L. Modification of rice starch using a combination of autoclaving and triple enzyme treatment: Structural, physicochemical and digestibility properties. Int J Biol Macromol. 2020; 144:500-508. https://doi.org/10.1016/j.ijbiomac.2019.12.112
37. Liang W, Liu X, Zheng J, Zhao W, Zheng Y, Ge X, Shen H, Ospankulova G, Muratkhan M, Zhainagul Kh K, Li W. Comparison study of DBD plasma combined with E-beam pre-and post-treatment on the structural-property improvement of Chinese yam starch. Food Bioproc Tech. 2023; 16(10):2287-2303. https://doi.org/10.1007/s11947-023-03024-1
38. Lockwood C, Munn Z, Porritt K. Qualitative research synthesis: methodological guidance for systematic reviewers utilizing meta-aggregation. Int J Evid Based Healthc. 2015; 13(3):179-187. https://doi.org/10.1097/XEB.0000000000000062
39. Mathobo VM, Silungwe H, Ramashia SE, Anyasi TA. Effects of heat-moisture treatment on the thermal, functional properties and composition of cereal, legume and tuber starches—a review. J Food Sci Technol. 2021; 58(2):412-426. https://doi.org/10.1007/s13197-020-04520-4
40. Mowafy S, Liu Y. Novel and conventional steam blanching impacts on potato starch digestibility and physicochemical properties. Food Bioproc Tech. 2024; 17(12):5066-5082. https://doi.org/10.1007/s11947-024-03434-9
41. Najib T, Heydari MM, Tu K, Meda V. Modification in starch structure of soaked and germinated lentil seeds under various thermal processing methods, including conventional, microwave, and microwave-assisted techniques. Food Chem Adv. 2023; 2:100267. https://doi.org/10.1016/j.focha.2023.100267
42. Nunes GT, Frasson SF, Zimmer TB, da Costa DA, Colussi R, Borges CD, Gandra EA, Mendonça CR. Avocado oil used to modify rice starch and prepare gluten-free cakes: physical–chemical, microbiological, sensory, and nutritional evaluations. Int J Food Sci Technol. 2024; 59(12):9287-9297. https://doi.org/10.1111/ijfs.17563
43. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, Shamseer L, Tetzlaff JM, Akl EA, Brennan SE, Chou R. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021; 372. https://doi.org/10.21860/medflum2021_264903
44. Palavecino PM, Penci MC, Ribotta PD. Impact of chemical modifications in pilot-scale isolated sorghum starch and commercial cassava starch. Int J Biol Macromol. 2019; 135:521-529. https://doi.org/10.1016/j.ijbiomac.2019.05.202
45. Park S, Kim YR. Clean label starch: production, physicochemical characteristics, and industrial applications. Food Sci Biotechnol. 2021; 30(1):1-7. https://doi.org/10.1007/s10068-020-00834-3
46. Pertiwi SR, Aminullah, Rajani RU, Novidahlia N. Effect of heat-moisture treatment on the physicochemical properties of native canistel starch. Food Sci. Technol. 2022; 42:e103921. https://doi.org/10.1590/FST.103921
47. Prestes RC, Silva LB, Torri AM, Kubota EH, Rosa CS, Roman SS, Kempka AP, Demiate IM. Sensory and physicochemical evaluation of low-fat chicken mortadella with added native and modified starches. J Food Sci Technol. 2015; 52(7):4360-4368. https://doi.org/10.1007/s13197-014-1496-2
48. Punia Bangar S, Ashogbon AO, Singh A, Chaudhary V, Whiteside WS. Enzymatic modification of starch: A green approach for starch applications. Carbohydr. Polym. 2022; 287:119265. https://doi.org/10.1016/j.carbpol.2022.119265
49. Raj N, Dalal N, Bisht V, Dhakar U. Potato starch: novel ingredient for food industry. Int J Curr Microbiol App Sci. 2020; 9(1):1718-1724. https://doi.org/10.20546/ijcmas.2020.901.190
50. Ren J, Chen S, Li C, Gu Z, Cheng L, Hong Y, Li Z. A two-stage modification method using 1, 4-α-glucan branching enzyme lowers the in vitro digestibility of corn starch. Food Chem. 2020; 305:125441. https://doi.org/10.1016/j.foodchem.2019.125441
51. Rostamabadi H, Bajer D, Demirkesen I, Kumar Y, Su C, Wang Y, Nowacka M, Singha P, Falsafi SR. Starch modification through its combination with other molecules: Gums, mucilages, polyphenols and salts. Carbohydr. Polym. 2023; 314:120905. https://doi.org/10.1016/j.carbpol.2023.120905
52. Saeva K, Srikaeo K, Sopade PA. Understanding starch digestibility of rice: a study in white rice. Int J Food Sci Technol. 2023; 58(9):4849-4859. https://doi.org/10.1111/ijfs.16599
53. Samarakoon ER. Impact of physical modifications on starch nutritional fractions: Rapidly digestible starch, slowly digestible starch and resistant starch. J Food Bioact. 2020; 12. https://doi.org/10.31665/jfb.2020.12249
54. Santos NC, Almeida RL, Brito AC, Silva VM, Albuquerque JC, Saraiva MM, Santos RM, De Sousa FM, Ribeiro VH, Carvalho RD, Moura HV. Effect of pulse electric field (PEF) intensity combined with drying temperature on mass transfer, functional properties, and in vitro digestibility of dehydrated mango peels. J Food Meas Charact. 2023; 17(5):5219-5233. https://doi.org/10.1007/s11694-023-02036-x
55. Sartori A.G.d.O., Saliba A.S.M.C., Bitencourt B.S., Guedes J.S., Torres L.C.R., Alencar S.M.d., Augusto P.E.D. Anthocyanin bioaccessibility and anti-inflammatory activity of a grape-based 3D printed food for dysphagia. Innov. Food Sci. Emerg. 2023; 84:103289. https://doi: 10.1016/j.ifset.2023.103289.
56. Šárka E, Sinica A, Smrčková P, Sluková M. Non-traditional starches, their properties, and applications. Foods. 2023; 12(20):3794. https://doi.org/10.3390/foods12203794
57. de Oliveira Sartori AG, Saliba AS, Bitencourt BS, Guedes JS, Torres LC, De Alencar SM, Augusto PE. Anthocyanin bioaccessibility and anti-inflammatory activity of a grape-based 3D printed food for dysphagia. Innov Food Sci Emerg Technol. 2023; 84:103289. https://doi.org/10.1016/j.ifset.2023.103289
58. Scott G, Awika JM. Effect of protein–starch interactions on starch retrogradation and implications for food product quality. Compre Rev Food Sci Food Saf. 2023; 22(3):2081-2111. https://doi.org/10.1111/1541-4337.13141
59. Shah A, Masoodi FA, Gani A, Ashwar B. Dual enzyme modified oat starch: Structural characterisation, rheological properties, and digestibility in simulated GI tract. Int J Biol Macromol. 2018; 106:140-147. https://doi.org/10.1016/j.ijbiomac.2017.08.013
60. Shah A, Wang Y, Tao H, Zhang W, Cao S. Insights into the structural characteristics and in vitro starch digestibility on parboiled rice as affected by ultrasound treatment in soaking process. Food Chem: X. 2023; 19:100816. https://doi.org/10.1016/j.fochx.2023.100816
61. Song J, Jiang L, Qi M, Li L, Xu M, Li Y, Wang X, Zhang D, Wang C, Chen S, Li H. Influence of magnetic field intensity on the quality characteristics of steamed bread enriched with

potato pulp. Food Bioproc Tech. 2024;17(8):2326-2338. https://doi.org/10.1007/s11947-023-03268-x

62. Sun J, Sun L, Chen X, Raza H, Wu G, Liang Q, Ren X. Characterization of arrowhead-derived type 3 resistant starch prepared by ultrasound-assisted α-amylase degradation. J Food Qual. 2023; 2023(1):2301485. https://doi.org/10.1155/2023/2301485
63. Thakur K, Sharma S, Sharma R. Morphological and functional properties of millet starches as influenced by different modification techniques: A review. Starch-Stärke. 2023; 75(3-4):2200184. https://doi.org/10.1002/star.202200184
64. Thongkong S, Kraithong S, Singh J, Tangjaidee P, Yawootti A, Klangpetch W, Rachtanapun P, Rawdkuen S, Phongthai S. Pulsed Electric Field for Quick-Cooking Rice: Impacts on Cooking Quality, Physicochemical Properties, and In Vitro Digestion Kinetics. Processes. 2024; 12(11):2577. https://doi.org/10.3390/pr12112577
65. Vargas-León EA, Falfan-Cortes RN, Navarro-Cortez RO, Hernández-Ávila J, Castro-Rosas J, Gómez-Aldapa CA. Double chemical modification in rice starch: acid hydrolysis optimization process and phosphating. CyTA-J Food. 2019; 17(1):632-639. https://doi.org/10.1080/19476337.2019.1624623
66. Vidhyalakshmi R, Meera MS. Dry heat and ultrasonication treatment of pearl millet flour: effect on thermal, structural, and in-vitro digestibility properties of starch. J Food Meas Charact. 2023; 17(3):2858-2868. https://doi.org/10.1007/s11694-023-01832-9
67. Wang G, Wang D, Huang M. Effect of 10 MeV electron beam irradiation on the structure and functional properties of wheat starch. Food Biophys. 2023; 18(3):470-477. https://doi.org/10.1007/s11483-023-09787-6
68. Wang N, Dai J, Miao D, Li C, Yang X, Shu Q, Zhang Y, Dai Y, Hou H, Xu S. Influence of enzymatic modification on the basis of improved extrusion cooking technology (IECT) on the structure and properties of corn starch. Int J Biol Macromol. 2023; 253:127274. https://doi.org/10.1016/j.ijbiomac.2023.127274
69. Wang X, Huang L, Zhang C, Deng Y, Xie P, Liu L, Cheng J. Research advances in chemical modifications of starch for hydrophobicity and its applications: A review. Carbohydr. Polym. 2020; 240:116292. https://doi.org/10.1016/j.carbpol.2020.116292
70. Wang Z, Mhaske P, Farahnaky A, Kasapis S, Majzoobi M. Cassava starch: Chemical modification and its impact on functional properties and digestibility, a review. Food Hydrocoll. 2022; 129:107542. https://doi.org/10.1016/j.foodhyd.2022.107542
71. Wu TY, Sun NN, Chan Z, Chen CJ, Wu YC, Chau CF. Enhancement of digestion resistance and glycemic control of corn starch through conjugation with gallic acid and quercetin using the free radical grafting method. Processes. 2022; 10(12):2610. https://doi.org/10.3390/pr10122610
72. Wu Z, Qiao D, Zhao S, Lin Q, Zhang B, Xie F. Nonthermal physical modification of starch: An overview of recent research into structure and property alterations. Int J Biol Macromol. 2022; 203:153-175. https://doi.org/10.1016/j.ijbiomac.2022.01.103
73. Xiao L, Yu Y, Yang X, Wei Z, Han L. Physicochemical properties of ultrasound-pretreated pea starch and its inclusion complexes with lauric acid. Food Chem: X. 2023; 20:100879. https://doi.org/10.1016/j.fochx.2023.100879
74. Yang Z, McClements DJ, Xu Z, Meng M, Li C, Chen L, Qiu C, Long J, Jin Z. Carbohydrate-based functional ingredients derived from starch: Current status and future prospects. Food Hydrocoll. 2022; 131:107729. https://doi.org/10.1016/j.foodhyd.2022.107729
75. Yao F, Li C, Li J, Chang G, Wang Y, Campardelli R, Perego P, Cai C. Effects of different cooking methods on glycemic index, physicochemical indexes, and digestive characteristics of two kinds of rice. Processes. 2023; 11(7):2167. https://doi.org/10.3390/pr11072167
76. Ye P, Mao C, Song M, Liu T, Xie Y, Pang H, Chen X, Wang Y, Wang Y. Effect of endogenous proteins and lipids on yam flour during radio frequency explosion puffing: Characterization, microstructure, function, and in vitro digestibility. Food Chem. 2025; 464:141710. https://doi.org/10.1016/j.foodchem.2024.141710
77. Zailani MA, Kamilah H, Husaini A, Awang Seruji AZ, Sarbini SR. Starch modifications via physical treatments and the potential in improving resistant starch content. Starch-Stärke. 2023; 75(1-2):2200146. https://doi.org/10.1002/star.202200146
78. Zhang H, Wang H, Zhang Q, Wang T, Feng W, Chen Z, Luo X, Wang R. Fabrication and characterization of starch-lipid complexes using chain-elongated waxy corn starches as substrates. Food Chem. 2023; 398:133847. https://doi.org/10.1016/j.foodchem.2022.133847
79. Zhang H, Zhou X, He J, Wang T, Luo X, Wang L, Wang R, Chen Z. Impact of amylosucrase modification on the structural and physicochemical properties of native and acid-thinned waxy corn starch. Food Chem. 2017; 220:413-419. https://doi.org/10.1016/j.foodchem.2016.10.030
80. Zhang S, Wang Z, Zhou X, Song Y, Wang L, Tian H, Zhang D, Lü X, Liu F, Huang J, Zhang X. Insights into the regulation mechanisms of dual hydrothermal treatment on the structure and digestive characteristics of A-and B-type wheat starch granules. Food Res Int. 2025; 200:115448. https://doi.org/10.1016/j.foodres.2024.115448
81. Zhong Y, Xu J, Liu X, Ding L, Svensson B, Herburger K, Guo K, Pang C, Blennow A. Recent advances in enzyme biotechnology on modifying gelatinized and granular starch. Tren Food Sci Tech. 2022; 123:343-354. https://doi.org/10.1016/j.tifs.2022.03.019