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Advances in microwave-induced physical modification of flours: From structural changes to product development

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ABSTRACT

Cereal-based products are staple foods in most human diets worldwide. Starch, the main component of cereals, is commonly modified to enhance its functionality and overcome its functional limitations. Physical hydrothermal treatment assisted by microwave (MW) radiation has recently gained considerable attention as an energy-efficient and cost-efficient alternative to traditional thermal methods. While most studies have focused on starch modification, the direct modification of flours and whole grains has emerged as a promising strategy for producing more nutrient-dense ingredients with enhanced functionality. In this context, the role of proteins, the second major biopolymers, and the interplay between endogenous components in determining the behaviour of complex starchy matrices is of great interest. This review explores recent advances in MW treatment of flours and grains, with particular emphasis on the structural and functional changes in starch and proteins, and the implications of these changes for product development. MW treatment has been shown to effectively alter the morphology and structure of both biopolymers. This led to modifications in functionality that varied depending on the botanical source and treatment conditions. These modifications effectively enhance the quality of cereal-based food products, particularly gluten-free bread. Overall, MW technology offers a promising green strategy for developing customised, functional ingredients tailored to specific dietary needs, with growing relevance to broader applications in the food industry.

1. Introduction

Cereal and cereal-based products are staple foods in the majority of human diets, both in developed and developing countries, and constitute a major portion of dietary energy and nutrients (Wrigley, 2017). In the Western world, people typically consume bread, pasta, and pizza, whereas in the Eastern world, steamed bread, noodles, and rice are preferred (B. Zhang et al., 2021). According to data released by Statista (2023), 633 million tonnes of cereal-based products were consumed in 2023, and the projection is that this consumption will continue to grow until 2029 (809 million tonnes). Cereals are mainly composed of two biopolymers: starch (55–75 %) and protein (6–20 %) (Koehler & Wieser, 2013). The amounts and characteristics of these two components greatly influence the techno-functional properties of cereals and their behaviour in food product elaboration (B. Zhang et al., 2021).

Starch has been commonly modified to enhance its functionality and widen its range of applications using physical, enzymatic, and chemical techniques (BeMiller, 2018; Horstmann et al., 2017). These modified starches have been commonly used in food industry, being particular its interest for the developing of gluten-free products (Horstmann et al., 2017). Physical modification of starch has attracted increasing interest recently compared to chemical techniques, reflecting the growing trend to reduce chemically modified ingredients in favour of greener alternatives that are perceived by consumers as safer (Fonseca et al., 2021). Unlike chemical or enzymatic methods, physical modification does not require the addition of chemicals or biological reagents, and the resulting starches do not need to be labelled as “modified” (BeMiller, 2018). The aim of physical treatments is to change the structure of starch (granule morphology, crystallinity, swelling, gelatinisation, and retrogradation) to improve its physicochemical, nutritional, and functional attributes (Fonseca et al., 2021; Horstmann et al., 2017). Several physical modification techniques have been employed, including

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pregelatinization, heat-moisture treatment (HMT), annealing, ultrasonication, pulse electric field, high hydrostatic pressure, and extrusion, among others. Among these, HMT is the most studied method for physical modification of starch. This technique involves limited moisture content (MC) (10–35 %), high temperature (above the starch gelatinisation temperature), and varying exposure time (1–24h) (Fonseca et al., 2021; Iuga & Mironeasa, 2020). Among the existing techniques for performing HMT, microwave (MW) radiation has gained interest as an alternative technology for this type of physical modification. MW heating uses electric and magnetic fields to generate heat directly within materials by interacting with polar molecules, such as water, resulting in a faster heating that that of conventional HMT (Tao et al., 2020; Villanueva et al., 2018). MW processes have demonstrated approximately 70 % heating efficiency, compared to only about 10 % for conventional hot-air ovens, while also providing more uniform heating at a faster rate and reducing temperature gradients (Khashaba et al., 2025). In this way, MW treatment represents a more sustainable approach, as it avoids the use of reagents and the generation of waste associated with chemical and biological modifications, while presenting a high energy efficiency and shorter processing times than conventional HMT, making it a cost-effective and environmentally friendly alternative (Solaesa et al., 2021). Several researchers have documented the effects of MW treatment on the functional, nutritional, chemical, and physicochemical properties of cereal starches. This growing interest is evident from the progressive increase in scientific publications indexed in the Scopus database that include the terms "Microwave," "Treatment," and "Starch" in the title, abstract, or keywords, rising from 15 publications in 2015 to 43 in 2020, and 92 in 2023.

Recently, interest in performing MW treatment in more complex starchy matrices, including whole flour and grains, instead of starch to obtain a functional ingredient with a better nutritional profile has increased. Some authors have investigated the application of MW treatments to cereals, including rice (Solaesa et al., 2021; Villanueva et al., 2018), tef (Calix-Rivera et al., 2023; Náthia-Neves et al., 2023), maize (An et al., 2023; Hançerlioğulları et al., 2023), wheat (Lamacchia et al., 2016; Tok & Tuncel, 2024), millet (Rao et al., 2023; Zhi et al., 2022), and sorghum (Vicente, Villanueva, et al., 2025). Pseudocereals, such as quinoa, buckwheat, and amaranth have also been investigated (Vicente et al., 2023a, Vicente, Mauro, et al., 2025; Vicente, Villanueva, et al., 2025). The modification of flour or grains entails changes not only to the starch but also to the other constituent components. Therefore, MW modification of protein, the second major polymer in flour, has been included in most of this research as a point of interest. In addition, the interactions between starches and proteins can greatly influence the modifications in flour properties, as it has been shown that these interactions may be more important than the physicochemical properties of the individual components (B. Zhang et al., 2021).

The modifications obtained with MW treatment have shown to depend on several factors, with sample temperature, moisture content (and its evolution during treatment), and exposure time being particularly critical. The specific temperature–moisture profile at each moment of the treatment largely determines the type and extent of modifications (Vicente, Villanueva, et al., 2025; Villanueva et al., 2018). These conditions can be modulated by MW design and operation, for example by adjusting the specific MW power (W/g), using hermetic containers that control pressure and moisture, or ensuring sample movement for homogeneous treatment. However, controlling and consistently reporting these parameters remains technologically challenging and most literature lack of detailed information, particularly when domestic MW equipment without modifications was used.

This review critically examines recent advances in MW treatment of complex starchy matrices, with particular emphasis on the modification of their two primary biopolymers: starch and protein. It explores the effects of MW treatment on structural properties, functionality, and *in vitro* digestibility of these components, while also addressing the interactions among them. Furthermore, the application of MW-modified flours in the formulation of cereal-based products is discussed, highlighting their potential to improve product physical and nutritional quality. By bridging molecular-level modifications with food system performance, this review underscores the growing relevance of MW technology as a sustainable and industry-applicable strategy for clean-label ingredient development.

2. Impact of microwave treatment on the morphology and structure of starchy matrices

2.1. Morphological properties

The morphology and distribution of starch and protein in flours depend on the botanical source, and can be significantly modified by MW, with different effects depending on the treatment conditions. Morphological changes in starch and protein after MW treatment have been studied using several microscopic techniques, including scanning electron microscopy (SEM) (An et al., 2023; Jin et al., 2022; Vicente, Villanueva, et al., 2025; Villanueva et al., 2018), confocal laser scanning microscopy (CLSM) (Náthia-Neves et al., 2023; Zhong et al., 2019), and atomic force microscopy (AFM) (Huang et al., 2022). In addition, the particle size was measured using laser diffraction for flour particles and starches (Tian et al., 2023; Vicente et al., 2023a; Vicente et al., 2023b), and dynamic light scattering (DLS) for proteins (Huang et al., 2022; Jin et al., 2022).

Particle aggregation has been observed to be frequent outcome of MW treatment. An et al. (2023) reported an increase in the particle size after MW treatment and milling of maize grains. These changes were attributed to the formation of larger agglomerates, as observed by SEM, which resulted from the partial melting and swelling of starch granules, along with the denaturation and aggregation of proteins. Similar results were observed by Calix-Rivera et al. (2023) for tef flour and by Vicente et al. (2023a) for buckwheat grains, with agglomeration and visual changes increasing with higher MC during treatment. Solaesa et al. (2022) observed a great influence of the MC, maintained during the entire treatment, on rice flour samples. Treatment at 8 % MC resulted in a cracked-out structure, with numerous small holes and no discernible granules, probably because the unfolded protein was spread over the starch granule surface. However, treatment at 30 % resulted in a more degraded microstructure with cavities and aggregated starch granules, which lost their integrity and polygonal shape. Similar effects were observed for the 20 % and 30 % MC treatments of rice flour, with MC being variable during treatment because it was performed in non-hermetic containers. These effects were related to amylose exudation, partial pasting, and protein spreading (Villanueva et al., 2018). The effect of treatment time on starch appearance was evaluated for quinoa flour by performing short treatments of 10–60 s (Cao et al., 2023). These authors observed that the original starch aggregates present in quinoa were first dispersed into separated particles; however, as the treatment time increased, the particles started to partially gelatinise and form larger aggregates and a more rigid structure. Fig. 1 illustrates the aforementioned modifications reported after MW treatment with SEM and CLSM, in this case for flour treatment of various matrices (amaranth, buckwheat, quinoa, and sorghum). Disruption of the native structure, with partial fusion and loss of integrity of the constituents, can be observed with both microscopy techniques (see Fig. 1). Vicente, Villanueva, et al. (2025) found that MW treatment performed on flour form resulted in greater particle size compared to treatment on grain form under the same conditions, highlighting the potential of treating grains instead of flour to minimise the formation of large agglomerates.

Several observations have been made regarding the morphological changes in MW-treated starch. Microwaved rice resulted in the modification of granule morphology towards less polygonal structures, which was associated with the disruption of the inner crystalline structure and, when high temperatures were achieved, partial gelatinisation occurred (Guo et al., 2019; Han et al., 2021). The impact of the treatment on

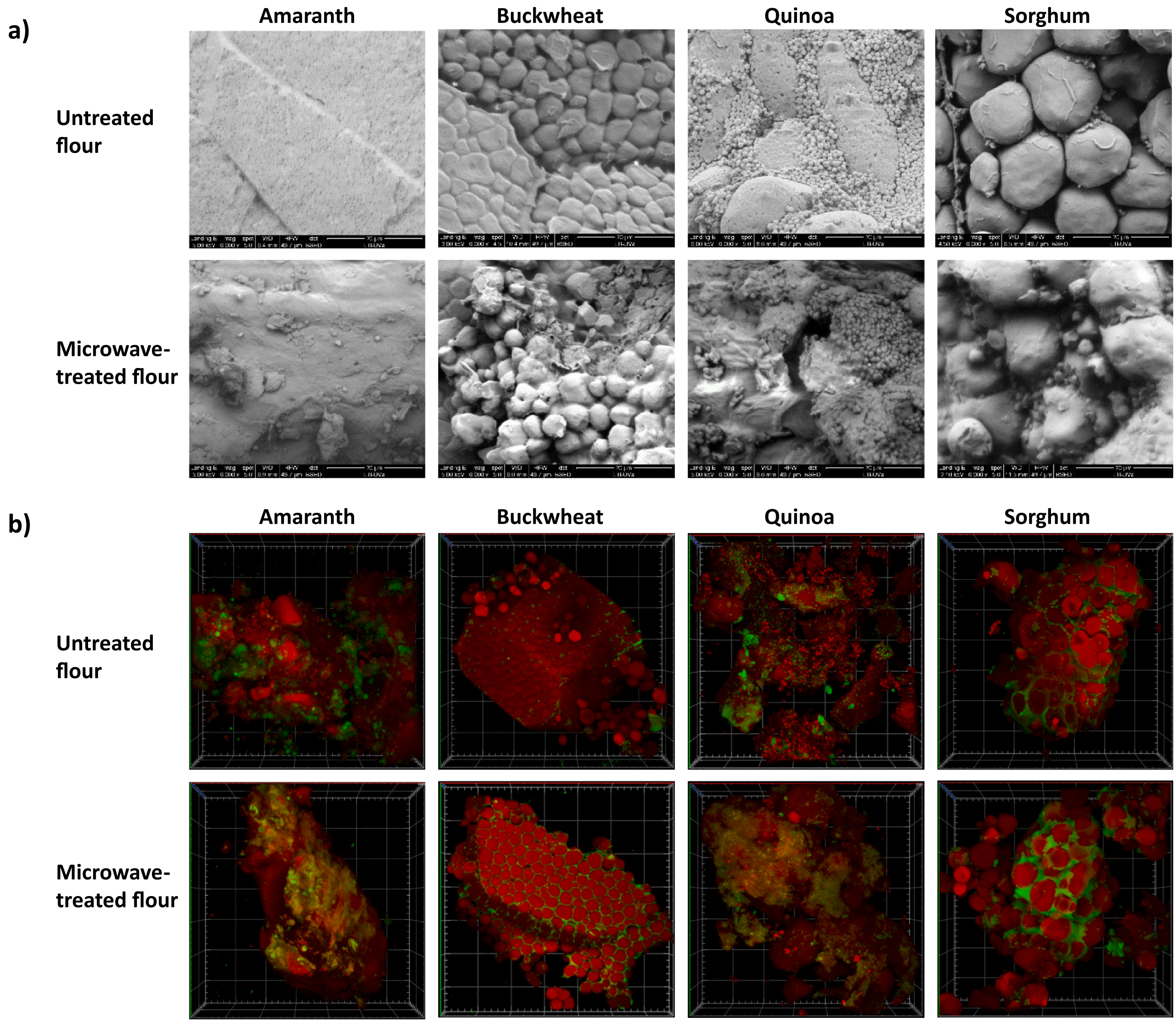

Fig. 1. Morphological changes in amaranth, buckwheat, quinoa, and sorghum flours following microwave treatment (25 % moisture content, 100 °C, 30 min). (a) Scanning electron microscopy (SEM) images at 6000 × magnification, adapted from Vicente, Villanueva, et al. (2025). (b) Confocal laser scanning microscopy (CLSM) images, where carbohydrates appear in red and proteins in green; scale bars represent 20 μm × 20 μm squares, adapted from Vicente, Mauro, et al. (2025). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

starch morphology was more pronounced when the sample was subjected to rapid heating (constant power of 300 W) than when it was subjected to a slower heating process (constant power of 100 W) to reach the same temperature (Han et al., 2021). Xu et al. (2019) reported a greater vulnerability of the hilium to MW radiation and related it to being a more amorphous and less ordered part of the starch granule. The amylose content was also shown to have a significant effect on starch modification with MW radiation. Tian et al. (2023) reported the formation of a porous structure with cracks and holes in normal and waxy maize starches, but not in high amylose maize starches. These results agree with those of Zhong et al. (2019), who also observed no disruption of starch granules after sort-time MW treatment of high amylose maize starch. However, these authors found a reduction in the fluorescence intensity observed in CLSM images for treatments longer than 2 min, indicating the presence of more compact and inaccessible structures. Fig. 1 illustrates some of the starch modifications induced by MW treatment, including amylose leaching and partial structural fusion associated with partial gelatinisation of starch granules (Vicente, Mauro, et al., 2025; Vicente, Villanueva, et al., 2025). The extent of these modifications varied with the botanical origin of the starch: matrices with smaller granules (amaranth and quinoa) formed diffuse, indistinct aggregates, whereas those with larger granules (sorghum and buckwheat) exhibited only minor changes in granule shape and surface characteristics (Vicente, Mauro, et al., 2025; Vicente, Villanueva, et al., 2025).

Regarding the specific effect of MW treatment on protein morphology, tef flour subjected to MW treatment was evaluated using CLSM, which revealed clear protein aggregation in treatments longer than 2 min at temperatures exceeding 70 °C (Náthia-Neves et al., 2023). Sun et al. (2020) reported a loss in starch granular structure and interactions with protein-forming clusters of larger sizes and rough surfaces in MW-treated pigeon pea flour. In addition, these authors isolated the treated protein and observed a fragmented structure with a reduction in its individual particle size, which may have led to more cleavage sites for interaction with other components. In contrast, MW-treated quinoa and buckwheat proteins have shown increased particle size, attributed to aggregation and disulfide bond formation during thermal treatment (Huang et al., 2022; Jin et al., 2022).

Vicente, Mauro, et al. (2025) related CLSM observations of a spread protein network surrounding starch granules after MW treatment with the increased disorder in protein secondary structure detected by FTIR. They proposed that the exposure of reactive groups in unfolded and/or denatured proteins promotes their dispersion and adhesion, leading to protein–protein and protein–starch agglomerates. This is consistent with the findings of Cao et al. (2025) for MW-treated oat starch-protein mixtures, who suggested that protein-starch linkages are likely mediated by hydrogen bonds: the abundant –OH groups of starch can interact with polar groups of protein side chains, as well as with the amine and carbonyl groups of protein backbones, facilitating hydrogen bond formation under MW heating. This effect was reported to be enhanced by doing MW treatment as compared to conventional heating in a water bath (Cao et al., 2025).

2.2. Structural properties

The effects of MW radiation on the structural properties of the main flour biopolymers, starch and protein, were assessed using various techniques. As shown in Table 1, the crystalline and lamellar structures of starch were analysed by X-Ray Diffraction (XRD), small-angle X-ray scattering (SAXS), and wide-angle X-ray scattering (WAXS). Their molecular structures were determined by size exclusion chromatography (SEC), gel permeation chromatography (GPC), high-performance anion-exchange chromatography coupled with a pulsed amperometric detector (HPAEC-PAD), ^{1}H Nuclear Magnetic Resonance (^{1}H NMR), and Fourier Transform Infrared Spectroscopy (FTIR). Protein secondary structure was studied by FTIR and circular dichroism (CD), and tertiary structure was assessed via UV absorption spectrum and intrinsic fluorescence. The free sulfhydryl groups, disulfide bonds (SS), surface hydrophobicity (H_0), and Z-potential were also evaluated. The key findings of the structural changes in starch and proteins are summarised in Table 1.

MW treatment caused structural damage to the starch structure. In general, starch crystallinity was reduced after MW treatment under HMT conditions, as observed by several authors (Han et al., 2021; Tian et al., 2023; Xu et al., 2019; Yang et al., 2017; Zhi et al., 2022). This effect was accentuated by longer treatment times (Tian et al., 2023; Zhong et al., 2019), higher MW power (Tian et al., 2023), and higher MC (Zhi et al., 2022). Tian et al. (2023) reported that low amylose maize starches exhibited a more pronounced reduction in crystallinity compared to high-amylose starches, relating the decrease with the degradation of connector chains between the double helix and backbone chains and disordered alignment of the double helices. A greater susceptibility to hydrolysis of α-(1,6) glycosidic bonds during MW treatment has been observed, and this was linked to the larger steric hindrance and stability of α-(1,4) glycosidic bonds (Xu et al., 2019; Yang et al., 2017). Yang et al. (2017) reported amylopectin with a reduced molecular weight, fewer short A chains, and increased short B1, long B2, and B3 chains after MW treatment. Samples with reduced starch crystallinity also exhibited a decrease in the thickness of crystalline lamellae (Tian et al., 2023; Zhong et al., 2019) and a reduction in double helix content (Han et al., 2021; Xu et al., 2019). Xu et al. (2019) proposed that during MW treatment the double and single helices may either be broken down into an amorphous phase directly or dissociate into single chains, which can subsequently be rearranged into new double and single helices if there is low steric hindrance. Han et al. (2021) reported that rapid MW heating caused more significant damage to starch granules than slow MW heating due to intensive friction, collision, and rapid water evaporation, leading to greater structural destruction of the starch linkages and internal crystalline regions. In addition, the FTIR results of several MW-treated grains and flours indicated a reduction in the short-range molecular order and an increase in the proportion of amorphous to crystalline structures (An et al., 2023; Calix-Rivera et al., 2023; Solaesa et al., 2022; Vicente et al., 2023b; Zhi et al., 2022).

It should be noted that depending on starch characteristics and MW conditions, increased crystallinity has also been reported in several studies. In most cases it has been related to the modification from a looser type B crystalline structure to a denser type A polymorph (Tao et al., 2020). However, some studies on A-type starches have also reported slight increases in crystallinity under mild MW conditions (moderate temperature, moisture, and/or time), whereas more intense treatments generally led to decreases. Zhong et al. (2019) found that a 1-min short MW treatment at 400 W/g and 30 % MC could enhance the relative starch crystallinity and lamellar peak intensity despite the partial breakage of short amylopectin and intermediate amylopectin chains, although longer treatment resulted in decreased crystallinity. Slight increases in crystallinity have been observed for rice flour (Solaesa et al., 2022) and quinoa flour (Vicente et al., 2023b) treated in hermetic containers at 20 % MC for 8 min at 18W/g and 9W/g, respectively, whereas no differences or decreases were observed for the rest of operating conditions including higher temperatures and/or MC and the use of systems that allowed water to scape during treatment. For those samples, the effects on crystallinity were also related to an increased V-type crystallinity, which was associated with amylose-lipid complexes and could enhance the total relative crystallinity of the treated flour samples (Solaesa et al., 2022; Vicente et al., 2023a; Villanueva et al., 2018).

Structural modifications of proteins after MW treatment have received less attention than starch modifications. However, recent research on whole flours/grains has highlighted the need for further investigation of the effect of MW on this biopolymer. Náthia-Neves et al. (2023) reported lower extractability and modified solubility of tef protein fractions, especially albumins and globulins, particularly when increasing MW time and flour MC. SDS-PAGE analysis showed a reduced band intensity after MW treatment (Náthia-Neves et al., 2023; Sun et al., 2020), which may be related to increased disulphide bond formation and decreased water solubility (Sun et al., 2020). Protein unfolding was also observed, as protein secondary structures were reported to become more disordered and flexible, with reductions in ordered structures increasing disordered conformations (Calix-Rivera et al., 2023; Jin et al., 2022; Rao et al., 2023; Solaesa et al., 2022; Sun et al., 2020). Huang et al. (2022) observed a greater impact of MW treatment on protein structure compared to traditional hydrothermal treatment, with MW accelerating protein denaturation and unfolding, exposing more hydrophobic residues and increasing surface hydrophobicity. These changes facilitated protein aggregation, accompanied by a marked reduction in free sulfhydryl groups and solubility. Similar effects, including increased Z-potential and disulfide bond content, were reported for pigeon pea flour (Sun et al., 2020). In soybean protein, Y. Wang et al. (2023) reported that short-term MW treatment disrupted non-covalent interactions and partially unfolded protein structures, exposing hydrophobic regions and free thiol groups. This facilitated intermolecular interactions, including disulfide bond formation and hydrophobic aggregation, leading to protein network reorganisation and aggregation. Longer MW exposure enhanced these effects through dipole alignment and thermal aggregation, promoting further cross-linking between protein molecules. However, Jin et al. (2022) reported different results when studying MW-treated buckwheat protein at different combinations of power and time. Short and low intensity treatments increased disulfide bond content; while long and/or high intensity treatments had the opposite effect, reducing disulfide bond content and increasing reactive sulfhydryl bond content. These effects may result from MW-induced molecular vibrations of the backbone of polypeptide chains and the action of polarised dipolar water molecules breaking protein disulfide bonds. In addition, those samples showed reduced Z-potential and an increased particle size, which was attributed to electrostatic bonding of proteins. These contrasting findings highlight that MW-induced protein aggregation can proceed through multiple mechanisms (disulfide bonding, hydrophobic interactions, and electrostatic forces) depending on protein source, MW conditions, and the presence of other flour components.

Table 1
Effects of microwave treatment on starch and protein structure.

Material	Treatment conditions	Methods	Major findings	Reference
Starch				
Normal, waxy, and high amylose maize starch	40, 80 and 120 W/g; 0.5, 1 and 1.5 min; 30 % MC; Modified domestic MW	SEC-dRI, HPAEC-PAD, WAXS, SAXS	The structure of maize starch with high amylose content (58 %) was practically unaffected by MW, while for the ones with <45 % amylose the amylopectin molecules degraded, the thickness of crystalline lamellae decreased, and the crystallinity decreased.	Tian et al. (2023)
Waxy maize starch	160 W/g; 10, 15 and 20 min; 30 % MC; Domestic MW	GPC-MALS, HPAEC-PAD, ^{1}H NMR, XRD	MW treatment yielded amylopectin with fewer short A chains and more short B1 and long B2 and B3 chains, reduced molecular weight and relative crystallinity, and preferential cleavage of α-(1,6) glycosidic bonds.	Yang et al. (2017)
High amylose maize starch	400 W/g; 1, 2, 3 and 4 min; 30 % MC; Laboratory MW	GPC, FACE, WAXS, SAXS	1-min treatment partially broke short amylopectin and intermediate amylose chains, enhancing relative crystallinity and lamellar peak intensity. Longer treatments reduced crystallinity and lamellar peak intensity without further breaking down starch molecules.	Zhong et al. (2019)
Normal maize and potato starch	2.06 and 6.63 W/g; 5 min; 30 % MC; Domestic MW	^{1}H NMR, ^{13}C NMR, XRD	MW caused structural damage, reducing crystallinity, double helices content, and degree of branching, with more destructive effects on PS (B-type) than NMS (A-type).	Xu et al. (2019)
Rice starch	400 and 1200 W/g; time to reach 100, 120, 140 and 160 °C; 30 % MC; Laboratory MW	FTIR, ^{13}C NMR, SAXS, XRD	MW reduced starch crystallinity and content of double helices. Rapid heating caused more significant damage to starch granules than slow heating due to intensive friction, collision, and rapid water evaporation, leading to greater structural destruction of the starch linkages and internal crystalline region.	Han et al. (2021)
Protein				
Quinoa protein	15 W/g; 70, 80 and 90 °C for 30 min; 20 % w/v; Laboratory MW	CD, UV, intrinsic fluorescence, free SH, H_0	MW had a greater impact on protein structure compared to traditional hydrothermal treatment. MW accelerated protein denaturation and unfolding, exposing more hydrophobic residues and increasing surface hydrophobicity. The marked reduction in free sulfhydryl groups and solubility suggested that MW facilitated protein aggregate formation.	Huang et al. (2022)
Buckwheat protein	480, 720, 960 W; 1, 2, 3, 4, 5 min; 4 % w/v; Domestic MW	SDS-PAGE, FTIR, SS, free SH, Z-potential	MW treatment caused SS content loss, increased sulfhydryl content, protein denaturation, and β-turn transformation into β-sheet and disordered coil. The decrease in Z potential magnitude suggested that aggregation may have occurred due to electrostatic bonds.	Jin et al. (2022)
Flour/grain				
Maize grain	2, 3 and 4 W/g; 2, 3 and 4 min; 19 % MC; Industrial MW	FTIR, XRD	MW reduced starch's short-range order and relative crystallinity, while denaturing protein molecules by unfolding, separating, and rearranging their helix structure. Increased time and power intensified the effects.	An et al. (2023)
Millet grain	1200 W; 0.5, 1, 1.5, 2 and 2.5 min; 15, 20, 25, 30 and 35 % MC; Domestic MW	FTIR, XRD	MW disrupted the short-range ordered and crystalline structures of starch, with higher initial MC causing more starch damage than extending MW time.	Zhi et al. (2022)
Quinoa grain	9 W/g; 8 min; 10, 20 and 30 % MC; Modified domestic MW	FTIR, XRD	MW disrupted short-range molecular order of starch, with the effects being more pronounced with increasing MC during treatment and when the moisture was maintained constant throughout the treatment (hermetic systems).	Vicente et al. (2023b)
Rice flour	18 W/g; 8 min; 8, 13, 15, 20 and 30 % MC; Modified domestic MW	FTIR, XRD	MW of flour, especially at higher MC, decreased short-range molecular order and increased the amorphous to ordered structure ratio, and favoured the formation of random-coil, α-helix, and β-turn protein structures while diminishing low-frequency β-sheets.	Solaesa et al. (2022)
White and brown tef flours	18 W/g; 8 min; 15, 20 and 25 %; Modified domestic MW	FTIR, NMR	MW disrupted short-range molecular order more with increasing MC, without significantly affecting the degree of branching. Protein secondary structure changed, showing a significant decrease in β-sheet and an increase in random coil, indicating protein unfolding.	Calix-Rivera et al. (2023)
White and brown tef flours	18 W/g; 1, 2 and 6 min; 15 and 25 % MC; Modified domestic MW	Osborne fractionation, SDS-PAGE	Increasing MW time and MC, significantly influenced the extraction and solubility of protein fractions, especially albumins and globulins. SDS-PAGE analysis showed reduced band intensity in MW samples.	Náthia-Neves et al. (2023)
Millet flour	2.3, 2,8 and 3.1 W/g; 2, 4, and 6 min; 24 % MC; Domestic MW	FTIR, XRD	MW-induced denaturation decreased protein extractability and purity, and reduced its crystallinity. Additionally, the secondary structure of protein became more disordered and flexible.	Rao et al. (2023)
Pigeon pea flour	3 min; 20 % w/v; Domestic MW	SDS-PAGE, FTIR, Z-potential, SS, free SH, H_0	Microwave treatment reduced ordered structures (β-sheet), increased disordered structures (random coil), raised disulfide bond content and zeta potential, and diminished the visibility and intensity of protein bands in SDS-PAGE.	Sun et al. (2020)

The treatment conditions include power per gram of the sample (power only if data not provided), microwave exposure time, initial moisture content (MC) of the sample, and type of microwave equipment. SEC: size exclusion chromatography, GPC: gel permeation chromatography, HPAEC: high performance anion-exchange chromatography, PAD: pulsed amperometric detector, FACE: Fluorophore-assisted carbohydrate electrophoresis, XRD: X-Ray Diffraction, SAXS: Small Angle X-ray Scattering, WAXS: Wide Angle X-ray Scattering, NMR: Nuclear Magnetic Resonance, FTIR: Fourier Transform Infrared Spectroscopy, SDS-PAGE: Sodium dodecyl sulphate–polyacrylamide gel electrophoresis, SS: disulfide bonds, SH: sulfhydryl groups; H_0: surface hydrophobicity, CD: circular dichroism, UV: ultraviolet absorption spectrum, MW: microwave.

3. Impact of microwave treatment on the techno-functionality of starchy matrices

3.1. Thermal properties

The starch gelatinisation and retrogradation behaviour and protein thermal denaturation were studied using differential scanning calorimetry (DSC). Gelatinisation of starch is a thermally induced transition process during which the ordered single and double helices are disrupted, causing a shift from a crystalline to an amorphous state. The temperature at which the weakest crystallites in the starch granules begin to melt was referred to as the onset temperature (T_o), while the temperature at which the most perfect crystallites fully melt was designated as the endset temperature (T_e). The gelatinisation enthalpy (ΔH) reflects the content and stability of the double helices. Xu et al. (2019) reported an increase in gelatinisation temperatures (T_o, T_p, and T_e) and a reduction in ΔH with an increase in MW power for normal maize starch and potato starch. These authors related the increase in T_o to the preferential destruction of the relatively weak crystallites, and the increase in T_e to the formation of more stable crystallites and helical structure rearrangement during MW treatment. Similar results have been reported for waxy maize starch (Yang et al., 2017), guar seed flour (Manikpuri et al., 2024), and maize grains (An et al., 2023), in which higher gelatinisation temperatures were obtained with an increase in MW time; and for rice flour (Solaesa et al., 2022; Villanueva et al., 2018), tef flour (Calix-Rivera et al., 2023), quinoa grain (Vicente et al., 2023b), and buckwheat grain (Vicente et al., 2023a), where a greater impact was observed with an increase in MC. Yang et al. (2017) related this effect to the reduction in short chains and crystallinity and the increase in B3 long chains that can form longer double helices which will require higher temperatures for complete dissociation. Most of these studies also showed a decrease in ΔH, which was consistent with the disruption of the double helices present in the crystalline and non-crystalline regions of the granules (Xu et al., 2019; Yang et al., 2017). The loss of crystalline order observed by XRD correlated to the reduced ΔH, showing partial gelatinisation of starch during MW treatment (An et al., 2023; Vicente, Villanueva, et al., 2025). However, some studies did not observe a significant effect of MW on ΔH (Calix-Rivera et al., 2023; Cao et al., 2022), or only for the most intense MW conditions (higher time or moisture) (Solaesa et al., 2021; Vicente et al., 2023b; Villanueva et al., 2018). This suggests that mild MW treatment may cause only limited molecular rearrangements, preserving most of the crystalline domains, and thus leading to minimal changes in ΔH. The retrogradation of starch after seven days of storage under accelerated conditions (4 °C) has also been studied. No significant effects have been observed in some studies (Calix-Rivera et al., 2023; Solaesa et al., 2022). However, Villanueva, Harasym et al. (2018) reported an increase in the retrogradation extent of up to 35 % for rice flour treated at 30 % MC, and Vicente, Villanueva, et al. (2025) observed similar effects in buckwheat, quinoa, and sorghum grains and flours. This increased retrogradation could negatively affect the shelf life of the gels. The gelatinisation scan may reveal a second peak at higher temperatures, which is associated with the dissociation of the amylose-lipid complexes. Villanueva et al. (2018) reported a slight reduction in this peak for rice flour treated at 30 % MC, which was attributed to the greater difficulty in amylose leaching from the treated starch granules. Vicente et al. (2023a) observed an inability to reform the amylose-lipid peak after dissociation in the gelatinisation scan of treated buckwheat grains, linking this to the formation of amylose-polyphenol complexes. Vicente, Villanueva, et al. (2025) found a similar behaviour in sorghum and buckwheat grains treated with MW, but not when treated in flour form. In contrast, Cao et al. (2022) reported increased enthalpy of the amylose-lipid peak after MW treatment of quinoa flour for longer treatment times, indicating the strength and content of this complex. No effect on this peak was found for the MW treatment of rice flour (Solaesa et al., 2022) and tef flour (Calix-Rivera et al., 2023). These different results highlight the potential of MW treatment to modify flour characteristics in distinct ways, depending on the treatment conditions and the botanical origin of the flour.

However, the thermal properties of proteins have not been extensively studied in the context of MW treatment. Jin et al. (2022) evaluated the glass transition temperature of buckwheat protein isolates subjected to conventional heating and MW treatment. The authors found that the glass transition was still detectable after MW treatment, although the temperature at which it occurred differed, probably because of the effect of the heating mechanism on protein. In contrast, the samples that underwent traditional heat treatment did not show any detectable transition or peak, suggesting extensive denaturation. Gu et al. (2024) observed a gradual decrease in protein denaturation associated enthalpy of mung bean flour as the MW treatment temperature increased. These authors reported a greater susceptibility to the thermal degradation of proteins than starch. However, more comprehensive studies are needed to understand the thermal behaviour of proteins under MW treatment across different sources and conditions, particularly within complex matrices.

3.2. Hydration and emulsifying properties

Evaluating the techno-functional properties of flour is crucial for determining its possible food applications, particularly in the food industry. Enhanced water absorption capacity (WAC) is a commonly observed result of MW treatment across various flours and grains, including maize (An et al., 2023), tef (Calix-Rivera et al., 2023; Náthia-Neves et al., 2023), millet (Ananthu et al., 2023; Rao et al., 2023), rice (Solaesa et al., 2021), buckwheat (Vicente et al., 2023a), and quinoa (Vicente et al., 2023b). Solaesa et al. (2021) and Vicente et al. (2023a) observed that higher MC during treatment led to an enhanced WAC. This effect was attributed to the disruption of hydrogen bonds between the amorphous and crystalline regions of starch and a slight expansion of the amorphous region, which increased the hydrophilicity of the starch molecules (Solaesa et al., 2021). Similarly, Vicente, Villanueva, et al. (2025) reported a higher increment in WAC when MW treatment was performed in grain form than in flour form, due to the higher water retention within the grain during treatment. Ananthu et al. (2023) noted that increasing MW power and time gelatinised starch molecules due to the heat generated during MW treatment and improved the WAC of the flour. In addition, the unfolding of the protein structure during MW treatment can also improve the entrapment of water molecules (Mahalaxmi et al., 2022). The disruption of non-covalent bonds in proteins can result in increased exposure of hydrophilic domains, leading to enhanced water absorption (Mahalaxmi et al., 2022; Rao et al., 2023). Oil absorption capacity (OAC) is mainly related to the physical trapping of lipids through proteins (An et al., 2023). Both slight increases and decreases in OAC values were observed after MW treatment depending on botanical origin and treatment conditions. Certain treatment conditions would have enhanced the exposure of protein hydrophobic binding points, whereas other conditions would have hindered these points (An et al., 2023; Manikpuri et al., 2024; Rao et al., 2023; Vicente, Villanueva, et al., 2025). Nonetheless, the findings from these studies indicated that the effect of MW treatment on OAC was relatively limited.

MW treatment increased the swelling power (SP) of tef flour under several MC (15–25 %) and treatment times (2–8 min) (Calix-Rivera et al., 2023; Náthia-Neves et al., 2023), and rice flour at 8–30 % MC (Solaesa et al., 2021). The increase in SP has been attributed to the weakening of the intramolecular bonds between amylose and amylopectin molecules, reduced crystallinity, enhanced amylose-water interactions, and interactions of starch with proteins and lipids (An et al., 2023; Solaesa et al., 2021). Zhi et al. (2022) observed reduced SP for starch extracted from millet grains treated at 15–35 % MC for 90–150 s. These authors related the reduction in SP to the structural damage and long-chain rupture of amylopectin and the increase in intermolecular and intramolecular forces through hydrogen bonding. In the studies of Vicente et al. (2023a) on buckwheat grain and Vicente et al. (2023b) on quinoa grain, lower MC during treatment led to increased SP, while higher MC reduced the SP compared to the control sample. The reduced SP observed under intense MW treatments compared to mild MW treatments may be attributed to enhanced starch-protein interactions through hydrogen bonding or hydrophobic interactions, facilitated by the increased exposure binding points in partially gelatinised starch and denatured protein. These interactions will limit the interaction with water, thus decreasing SP. Though this mechanism has not been reported for MW treatment yet, it has been proposed for radio frequency treatment of corn grains, a related dielectric heating method operating at lower frequencies (Ren et al., 2024).

The emulsifying and foaming properties are mainly influenced by proteins; however, starch can also play a role in the process and affect the ability of proteins to form and stabilise emulsions and foams (Nawaz et al., 2018). MW treatment can both enhance and diminish the emulsifying and foaming properties of flours, depending on the matrix and the treatment conditions. Ananthu et al. (2023) showed no significant effect on foaming and emulsion capacities after MW treatment of white finger millet flour at various powers and times. Nawaz et al. (2018) reported that starch extracted from microwaved lotus flour exhibited enhanced emulsification properties, which were related to a decrease in granular size and an increase in surface area. Increased emulsifying capacity and stability were also observed for treated millet flour (Rao et al., 2023), for buckwheat grains treated at 13 % MC (Vicente et al., 2023a), and for the shortest treatments of lentil flour (Mahalaxmi et al., 2022). These authors attributed the enhanced emulsifying capacity to the partial unfolding of proteins, which led to increased exposure of hydrophobic groups and modifications in secondary structures, resulting in improved protein absorption at the oil-water interface. However, emulsion activity was decreased with longer treatments of lentil flour (Mahalaxmi et al., 2022) and guar seed flour (Manikpuri et al., 2024); and with higher MC for buckwheat grains (Vicente et al., 2023a). Náthia-Neves et al. (2023) observed a dependence of the emulsion properties of tef flours on time and MC during MW treatment. Treatments performed at a lower MC and time led to enhanced emulsifying properties, whereas longer treatments and increased MC diminished these properties. A reduction in foaming capacity and stability was the most common output after MW treatment of several flours (Mahalaxmi et al., 2022; Manikpuri et al., 2024; Náthia-Neves et al., 2023; Rao et al., 2023; Vicente et al., 2023b). These authors related this effect to the reduction in polar amino acids, protein denaturation, and formation of protein aggregates, which reduced diffusion and adsorption at the air–liquid interface. In flour systems, these effects may be further influenced by starch gelatinisation and protein–starch interactions, which can restrict protein mobility and aggravate the reduction in foaming capacity. However, Náthia-Neves et al. (2023) found enhanced foaming properties in tef flour treated for a short time at a low MC and Vicente et al. (2023b) for quinoa grains treated at 10 % MC in hermetic containers, highlighting mild treatment conditions may led to opposite results as reported for emulsifying properties.

3.3. Pasting properties

Pasting properties, commonly measured using a Rapid Visco Analyser, reflect the changes in apparent viscosity of starch suspensions during controlled heating, cooling, and agitation. Pasting properties of flours are critical for many of their applications in food industry. Table 2 summarises the main effects on pasting properties observed after MW treatment of several flours/grains under a variety of conditions. In general, the MW treatment led to lower viscosimetric profiles with delayed pasting, with a marked effect of MC, power, and time. Higher pasting temperature and reduced peak, trough, and breakdown viscosities were observed with increasing MC (Calix-Rivera et al., 2023; Villanueva et al., 2018), power (Manikpuri et al., 2024), and time (Manikpuri et al., 2024; Villanueva et al., 2018). A higher pasting temperature may be related to the enhanced resistance of starch to swelling and rupture owing to the strengthening of the intragranular bonding forces (Calix-Rivera et al., 2023). The reduction in peak viscosity can be attributed to the disruption of starch structure caused by MW treatment, which leads to decreased crystallinity, degraded amylopectin, and disruption of the double helical structure (Tian et al., 2023). The final viscosity and setback exhibited different trends, demonstrating both increases and decreases depending on the source and treatment conditions (see Table 2). The reduction in amylose leaching from starch granules as a consequence of the promotion of amylose-amylose and/or amylose-amylopectin chain interactions could explain the reduction in setback (Villanueva et al., 2018). However, an increased setback may be related to a decrease in the degree of branching, as more linear starch molecules reassociate quickly upon cooling, although protein interactions may also play a role (Gu et al., 2024).

Some samples treated with low MC showed the opposite behaviour after MW treatment. Lower pasting temperature was observed for rice flour treated 8 min at 3 % MC (Solaesa et al., 2021), and increased peak viscosity was reported for millet grain treated 0.5 min at 15 % MC (Zhi et al., 2022). A more extensive effect was observed for mung bean flour treated at 13 % MC, with a marked decrease in pasting temperature and increase in pasting profile (higher peak, trough, breakdown, final, and setback viscosities) (Gu et al., 2024). Vicente et al. (2023a) reported increased peak, though, final, and setback viscosities for buckwheat grains treated at 13 % MC in a hermetic container, while treating at higher MC led to the opposite trend. Similarly, Vicente et al. (2023b) observed increased pasting profiles for quinoa grain treatment at 10 % and 20 % MC in a non-hermetic container. These authors related the enhanced pasting profiles to the limited MC that prevented starch gelatinisation, together with the partially denatured and aggregated proteins that formed a viscoelastic network around the starch granules, altering their pasting properties. The reduction in pasting temperature can be related to the breaking of intra- or intermolecular hydrogen bonds in starches, facilitating swelling (Solaesa et al., 2021), and to the formation of a porous morphology (Cao et al., 2022).

4. Impact of microwave treatment on the digestibility of starchy matrices

4.1. Starch digestibility

Starch can be classified into three categories based on the rate of glucose release and absorption in the gastrointestinal tract: rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS). RDS refers to starch that can be digested and absorbed in the small intestine within 20 min, resulting in a pronounced and rapid increase in postprandial blood sugar levels. SDS refers to starch that can be fully digested within 20–120 min in the small intestine, thereby providing a longer-lasting sense of satiety. RS refers to starch that cannot be digested in the small intestine, but can be fermented in the large intestine to produce short-chain fatty acids, which have been found to be beneficial for human health (Gu et al., 2024).

The effects of MW treatment (under HMT conditions) on the *in vitro* digestibility of different flours and starches are presented in Table 3. From the available literature, different results were observed when an *in vitro* digestion method was applied to raw flours/starches compared to cooked ones (treated samples after gelatinisation in excess water).

The raw samples led to reductions in RS and increases in RDS, with the effects on SDS being dependent on the matrix and treatment conditions (Gu et al., 2024; Guo et al., 2019; Solaesa et al., 2022; Xu et al., 2019; Zhi et al., 2022). Guo et al. (2019) and Solaesa et al. (2022) observed for raw rice starch and flour, respectively, an increase in RDS and a concomitant decrease in RS with an increase in the MC employed for MW treatment. These authors related this behaviour to an increased modification of starch morphology and structure with an increase in MC. This effect has been commonly reported for the traditional HMT of starch, as reviewed by Zavareze and Dias (2011). Zhi et al. (2022) evaluated the effects of different treatment times and MC values on the MW treatment of millet grains. They observed increased damage to starch granules with increasing time and moisture, and related it to the increased susceptibility to enzymatic hydrolysis of raw samples. The reduction in RS to produce more SDS and RDS can also be related to the modification of starch structure with increased enzyme accessibility to hydrolysis due to an increase in the amorphous regions at the expense of a reduction in crystalline regions, a reduction in the chain packaging, and weakened helix alignment in crystalline lamellae (Guo et al., 2019; Solaesa et al., 2022). These structural transformations are visually summarised in Fig. 2, which presents the model proposed by Solaesa et al. (2022) describing the effects of MW treatment on rice starch granular structure as function of flour MC, and the resulting impact on *in vitro* starch digestibility of the raw, uncooked samples. In addition, Xu et al. (2019) reported that for starches with an "inside out" digestion pattern, such as normal maize starch, the modifications in crystalline and helical structures were the key factors affecting digestibility; however, for "exo-pitting" digestion pattern, such as potato starch, the variation in morphological structure may be the first factor influencing enzymatic hydrolysis.

However, the cooked samples showed the opposite effects, with an increase in RS or SDS and a reduction in RDS (Baah et al., 2024; Gu et al., 2024). For cooked high-amylose maize starch, short treatments led to increased RS, whereas longer treatments reduced RS (Zhong et al., 2019). Gu et al. (2024) and Zailani et al. (2022) compared the variation in RS of mung bean flour and sago starch, respectively, after MW treatment analysing the raw and the cooked treated samples. They observed a reduction in RS when analysis was performed on raw samples but an increase when performed on cooked samples. Gu et al. (2024) related it to three aspects: (1) The lower access of amylase to glycosidic bonds because of the recrystallization of debranched starch molecules with each other (resistant start type 3), and the formation of complexes with lipids (resistant starch type 5); (2) the formation of a protein network around starch granules acting as a physical barrier to enzyme access to starch; (3) the formation of a denser gel network with MW treatment. In line with this, Cao et al. (2025) reported that MW treatment of a starch–protein oat mixture in excess water enhanced slower digestibility compared to conventional water bath treatment. This effect was attributed to hydrogen bonding between peptide chains unfolded during MW treatment and starch molecules, which reduced the dissociation of starch double helix structures. Such interactions provide further mechanistic support to the denser gel network proposed by Gu et al. (2024) as a key factor underlying the reduced digestibility of cooked MW-treated samples.

Recently, MW treatment in excess water was reported to enhance of starch-polyphenol complex formation, as reported for lotus seed starch with chlorogenic acid (J. Wang et al., 2021). Other authors have also observed the possible formation of these complexes under limited water conditions (MC < 30 %) for MW-treated buckwheat and sorghum grains (Vicente et al., 2023a; Vicente, Villanueva, et al., 2025) and for MW-treated sorghum meal with non-tannin and tannin phenolic extracts (Baah et al., 2025). In lotus seed starch, MW treatment partially disrupted the granular, short-range ordered, helical, and lamellar structures, increasing molecular mobility and allowing chlorogenic acid to interact more effectively with starch molecules. This led to the formation of V-type inclusion complexes, non-inclusion complexes, and physically entrapped phenolic compounds (J. Wang et al., 2021). Starch–polyphenol complexes have been shown to increase RS content and promote a higher proportion of SDS, resulting in a reduced or slowed digestion and potential improvements in gut health (Raza et al., 2023). These effects are mainly attributed to the interactions between phenolics and starch forming complexes, the inhibition of α-amylase activity, and the formation of phenolic–protein barriers around starch granules, all of which hinder starch digestion (Baah et al., 2025).

4.2. Protein digestibility

The effects of MW treatment of flours or protein isolates on protein digestibility have been assessed in various studies, as summarised in Table 4. Both increases and decreases in protein digestibility have been reported after MW treatment depending on the botanical source and

Table 2
Effect of microwave treatment on pasting properties.

Material	Treatment conditions	MW effect						Reference
		PT	PV	TV	BV	FV	SV	
Brown tef flour	18 W/g; 8 min; 15, 20 and 25 %; Modified domestic MW	↑	↓	↓	↓	↓	↓	Calix-Rivera et al. (2023)
Rice flour	18 W/g; 8 min; 3 % MC; Modified domestic MW	↓	↓	ns	↓	ns	ns	Solaesa et al. (2021)
	18 W/g; 8 min; 8, 13 and 15 % MC	↑	↓	ns	↓	↑	↑	
	18 W/g; 8 min; 20 and 30 % MC	↑	↓	↓	↓	↓	↓	
Rice flour	9 W/g; 2, 4, and 6 min; 20 % MC; Modified domestic MW	↑	↓	↑	↓	ns	ns	Villanueva et al. (2018)
	9 W/g; 2, 4, and 6 min; 30 % MC	↑	↓	ns	↓	↓	↓	
	9 W/g; 8 min; 20 and 30 % MC	↑	↓	↓	↓	↓	↓	
Buckwheat grain	18 W/g; 8 min; 13 % MC; Modified domestic MW	↓	↑	↑	ns	↑	↑	Vicente et al. (2023a)
	18 W/g; 8 min; 20 % MC	ns	↓	↓	ns	↓	ns	
	18 W/g; 8 min; 25 and 30 % MC	↑	↓	↓	ns	↓	↓	
Millet grain – starch extracted	1200 W; 0.5 min; 15 % MC; Domestic MW	nd	↑	nd	ns	ns	ns	Zhi et al. (2022)
	1200 W; 1.5, 2 and 2.5 min; 15 % MC	nd	↓	nd	↓	↑	↑	
	1200 W; 1.5 min; 20, 25, 30 and 35 % MC	nd	↓	nd	↓	↓	↓	
Quinoa flour	9 W/g; 10 and 20 s; 12 % MC; Laboratory MW	ns	ns	ns	↓	ns	↓	Cao et al. (2022)
	9 W/g; 30 and 40 s; 12 % MC	ns	ns	ns	ns	ns	ns	
	9 W/g; 60s; 12 % MC	↓	ns	ns	↑	↑	↑	
Quinoa grain	9 W/g; 8 min; 10 % MC (open system); Modified domestic MW	↑	↑	↑	↓	↑	↑	Vicente et al. (2023b)
	9 W/g; 8 min; 20 % MC (open system)	↑	↑	↑	↓	↑	↑	
	9 W/g; 8 min; 30 % MC (open system)	↑	↓	↓	↓	↓	↑	
Guar seed flour	1 and 2 W/g; 6 min; natural MC; Domestic MW	↑	↓	↓	↓	↓	ns	Manikpuri et al. (2024)
	1, 2, 3 W/g; 9 min (and 3 W/g 6 min); natural MC	↑	↓	↓	↓	↓	↓	
Mung bean flour	6 W/g; time to achieve 100, 110, 120, and 130 °C; 13 % MC; Industrial MW	↓	↑	↑	↑	↑	↑	Gu et al. (2024)

The treatment conditions include power per gram of the sample (power only if data not provided), microwave exposure time, initial moisture content (MC) of the sample, and type of microwave equipment. MW effect: pasting parameter variation in treated samples compared with the native/untreated sample. PT: pasting temperature, PV: peak viscosity, TV: trough viscosity, BV: breakdown viscosity, FV: final viscosity, SV: setback viscosity. ↑ and ↓: statistically significant increases and decreases, respectively, compared to the untreated sample. ns: non-significant statistical modification versus control. nd: no data were provided by the original article.

treatment conditions. Moderate MW treatment has been shown to increase protein digestibility mainly through two mechanisms: (1) molecular rearrangement of proteins with protein unfolding and exposure of protease binding sites, and (2) reduction of particle size by protein hydrolysis, which results in increased surface exposure of more binding sites for protease activity (Jin et al., 2022; Sun et al., 2020). The reduction in antinutritional factors, such as trypsin inhibitor activity, may also have induced increased protein digestibility (Manikpuri et al., 2024). However, excessive heating may induce extensive protein denaturation, leading to aggregation and cross-linking, thus covering protease hydrolysis sites and reducing digestibility (Cao et al., 2023; Kamble et al., 2020). Moreover, the Maillard reaction may impede the activity of proteolytic enzymes and decrease digestibility through a process akin to cross-linking and aggregation (Kamble et al., 2020).

5. Effects of microwave treatment on the characteristics of cereal-based products

5.1. Rheological properties of gels made with microwave-treated flours

The rheological properties of the gels prepared with MW-treated flour have been evaluated through dynamic oscillatory tests: frequency sweep, strain sweep, and large-amplitude oscillatory shear (LAOS). MW treatment promoted gel stability and enhanced viscoelastic moduli, particularly for rice flour treated with 8 % and 20 % MC (Solaesa et al., 2021). The structuring effect of MW treatment on gels has also been reported for tef flour (Calix-Rivera et al., 2023; Lisovska, Banaś, et al., 2023), maize grains (An et al., 2023), and buckwheat flour (Lisovska, Banaś, et al., 2023). Vicente et al. (2024a) also observed the enhanced gel consistency and stability for MW treatment of buckwheat grains up to 25 % MC. However, treatment at 30 % MC led to gels with diminished elastic, viscous, and complex moduli, as well as reduced resistance to high strain stresses. This outcome was attributed to partial gelatinisation during MW treatment, which resulted in a less firm gel due to the partial collapse of the starch granule structure (Vicente et al., 2023a; Zavareze & Dias, 2011). An et al. (2023) reported the appearance of secondary loops in the LAOS test, which suggested that the gel structure underwent rearrangement and reorganisation, leading to a more flexible and complex microstructure. Gu et al. (2024) studied gels elaborated with MW-treated mung bean flour, observing that reduced branching facilitated starch molecule cross-linking, while moderately denatured protein formed starch-protein double network gels, enhancing gel strength and plasticity during LAOS test. They observed that mild to moderate denaturation of proteins (treatment at 100–120 °C) improved the uniformity of the gel network, but excessive denaturation and aggregation (treatment at 130 °C) decreased the uniformity, preventing further improvement of the gel properties.

5.2. Bread-making performance of microwave-treated flours

The development of gluten-free breads using MW-treated flour was also assessed. A summary of the measured properties and results is presented in Fig. 3. Pérez-Quirce et al. (2017) used MW-treated rice flour at different flour MC (13–25 %) and treatment times (0–4 min) to reduce flour β-glucanase activity and applied it to breadmaking. These treatments successfully reduced enzyme activity with increasing MC and time, thus enhancing the molecular weight of β-glucans in the final bread. In addition, these authors found a potential improvement in bread physical quality with treatment at the highest MC and time. Villanueva et al. (2019) evaluated the effect of replacing 30 % and 50 % of native rice flour by MW-treated one at 20 % and 30 % MC for 8 min on dough rheology and bread-making performance. These authors found enhanced dough viscoelasticity, resistance to deformation, and elastic behaviour with the inclusion of MW-treated flour. The resulting breads had a higher specific volume, softer crumb, and delayed staling. Villanueva et al. (2024) performed an optimisation study on the doses of

Table 3
Effect of microwave treatment on *in vitro* starch digestibility of flour and starch samples.

Material	Treatment conditions	Form	MW effect			Reference
			RDS	SDS	RS	
Sorghum flour (white, non-tannin)	12.5 W/g, 15 min, 25 % MC; Industrial MW	Cooked	↓	↓	↑	Baah et al. (2024)
Sorghum flour (red, tannin and non-tannin)	12.5 W/g, 15 min, 25 % MC; Industrial MW	Cooked	↓	↑	↓	Baah et al. (2024)
Mung bean flour	6 W/g; time to achieve 100, 110, 120, and 130 °C; Industrial MW	Cooked	↓	↓	↑	Gu et al. (2024)
Mung bean flour	6 W/g; time to achieve 100, 110, 120, and 130 °C; Industrial MW	Raw	↑	↑	↓	Gu et al. (2024)
High-amylose maize starch	400 W/g, 1 min; 30 % MC; Laboratory MW	Cooked	↓*	↓*	↑	Zhong et al. (2019)
High-amylose maize starch	400 W/g, 2, 3, 4 min; 30 % MC; Laboratory MW	Cooked	↑*	↑*	↓	Zhong et al. (2019)
Sago starch	180 W; 15 min; 57 and 20 % w/v; Domestic MW	Cooked	nd	nd	↑	Zailani et al. (2022)
Sago starch	180 W; 15 min; 57 and 20 % w/v; Domestic MW	Raw	nd	nd	↓	Zailani et al. (2022)
Rice flour	18 W/g; 8 min; 15, 20 and 30 % MC; Modified domestic MW	Raw	↑	↓	↓	Solaesa et al. (2022)
Millet grain	1200 W; 30, 60, 90, 120, and 150 s; 15, 20, 25, 30, and 35 % MC; Domestic MW	Raw	↑	↑	↓	Zhi et al. (2022)
Rice starch	8 W/g; 3 min; 15 and 35 % MC; Industrial MW	Raw	↑	↑	↓	Guo et al. (2019)
Maize and potato starch	2.06 and 6.63 W/g; 5 min; 30 % MC; Domestic MW	Raw	↑	↑	↓	Xu et al. (2019)

The treatment conditions include power per gram of the sample (power only if data not provided), microwave exposure time, initial moisture content (MC) of the sample, and type of microwave equipment. MW effect: variation in treated samples in comparison with the native/untreated sample. RDS: rapidly digestible starch. SDS: slowly digestible starch; RS: resistant starch. *RDS + SDS. ↑ and ↓: statistically significant increases and decreases, respectively, compared to the untreated sample. nd: no data were provided by the original article.

MW-treated rice flour, water level, and hydroxypropyl methylcellulose (HPMC) to improve the physical quality of gluten-free bread. The authors showed that replacing 50 % or 80 % of native rice flour with MW-treated flour allowed to reduce the usual HPMC dose by more than half, while obtaining a higher loaf volume and a softer crumb than their counterparts made with untreated flour and baked with the usual dose of additive (2 %). Garske et al. (2023) have also shown the ability of MW treatment to reduce additives (CMC, xanthan gum, and mono and diglycerides of fatty acids) by using MW treated casava starch and chickpea flour (20–40 % initial water content, 900W, 3–6 min). Vicente et al. (2024a) explored the substitution of 50 % rice flour with untreated and MW-treated buckwheat grains in gluten-free bread. The MW-fortified doughs exhibited higher consistency and withstood higher

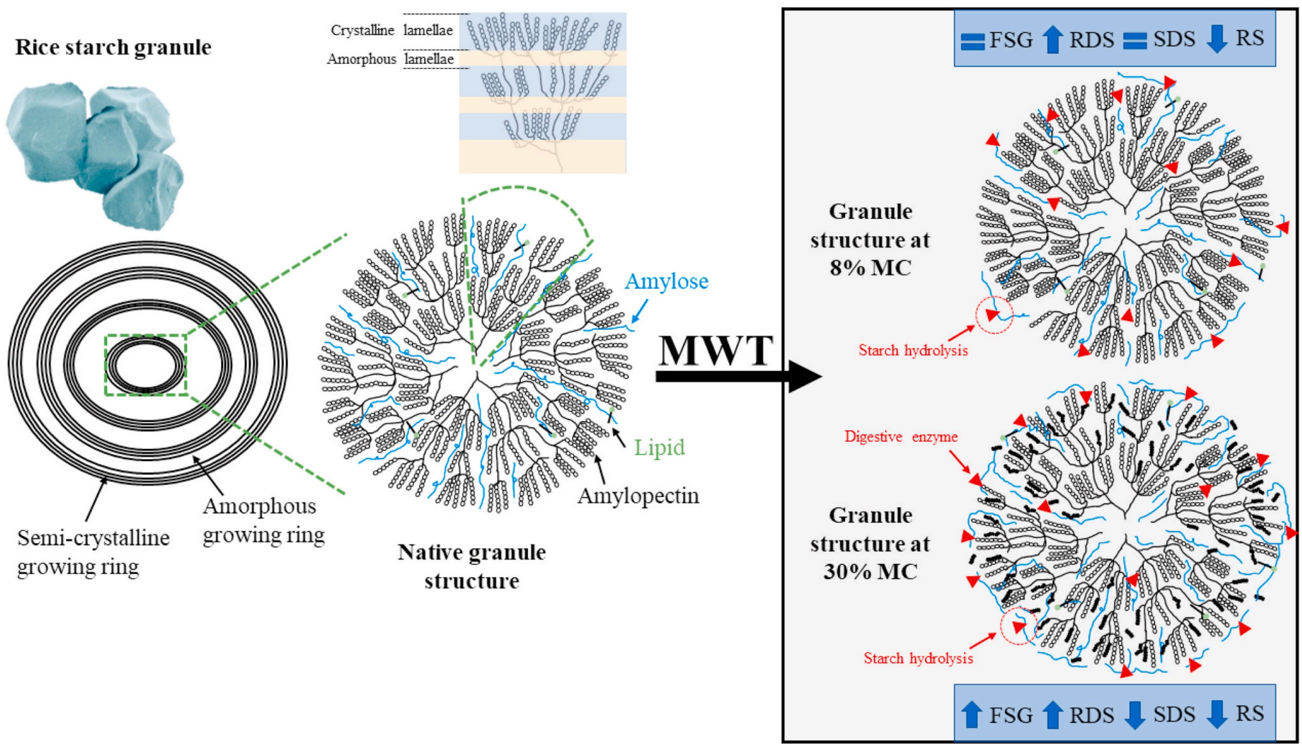

Fig. 2. Schematic representation of the internal structure of rice starch granules before and after microwave treatment. The native granule structure is depicted on the left, while the modified structures resulting from microwave treatment at 8 % moisture content (Granule structure at 8 % MC) and 30 % moisture content (Granule structure at 30 % MC) are shown on the right. Reproduced from Solaesa et al. (2022).

stresses for the same level of deformation, showing also higher viscosity and elastic recovery responses. This led to improved bread quality by increasing specific volume and reducing crumb hardness of breads with MW-treated flour compared to those with untreated buckwheat flour. Additionally, MW-treated breads reduced glucose release by up to 25 % and improved protein digestibility by up to 23 % during *in vitro* starch digestion. Vicente et al. (2024b) evaluated the use of untreated and MW-treated quinoa flour to replace maize starch at varying levels (0–75 %) in gluten-free bread. Increasing amounts of native quinoa flour reduced dough development and stability during fermentation test, but this effect was mitigated by using MW-treated quinoa flour at the same levels. As a result, MW-treated quinoa flour showed improved specific volume, reduced hardness, and delayed staling compared to untreated quinoa flour. It also reduced the herbaceous off-flavours associated with quinoa, enhancing the bread's sensory quality. Lisovska, Tyupova, et al. (2023) showed that MW treatment of buckwheat and teff flours (900 W, 8 min, 30 % MC) blended with untreated rice flour improved the nutritional profile of gluten-free breads by retaining higher levels of essential nutrients and bioactive compounds.

MW treatment has also been performed on wheat and composite flours containing wheat to modify wheat bread characteristics. Olcay and Ozulku (2025) prepared breads with flour mixes treated with microwaves (350 W–700 W and 30 s, 90 s, and 50 s) containing 50 % wheat flour and 50 % composite flours (barley, buckwheat and lupin). The resulting breads showed extended shelf life through reduced free fatty acid content and yeast-mould count, as well as increased total phenolic content and sensory acceptability compared to the same mixture without MW treatment. However, the physical quality of bread decreased, and the *in vitro* starch digestibility raised RDS. Lamacchia et al. (2021) applied flour obtained from MW-treated wheat kernels following their patented Gluten Friendly™ process in bread-making. MW-treated wheat induced marked changes in dough rheology, including higher water absorption, higher tenancy, and lower extensibility, yet breads produced from treated flours maintained good structure and sensory quality, comparable to conventional wheat bread. Morales-Huerta et al. (2025) prepared breads with MW treated wheat flour (13 % initial moisture, 3.2 W/g, 15–120s, household equipment). The obtained breads contained up to 50 % greater resistant starch and significantly reduced rapidly digestible starch, indicating improved nutritional profile of the final product.

5.3. *Other food applications of microwave-treated flours*

MW-treated flour has also been used to prepare other cereal-based products. MW-treated pearl millet flour was used to prepare rotis, being the treatment effective for reducing enzymatic activities related to rancidity, reducing RDS, and enhancing antioxidant capacity (Ali et al., 2023). MW treatment of sorghum grains was effective in producing porridge with reduced rancidity development during storage without any adverse effects on other quality attributes (Adebowale et al., 2020). Gluten-free muffin quality was successfully improved with MW-treated composite of corn starch and pea protein isolate (7:3) by Ha et al. (2025). MW treatment promoted starch–protein interactions, reducing retrogradation enthalpy up to 45 % and lowering gel viscosity. The resulting in muffins presented 33 % higher specific volume, softer texture, improved sensory attributes, and 40–50 % reduced hardness after three days of storage than those with untreated starch-protein composite.

Several authors have reported the influence of MW treatment on pasta and noodles. Padalino et al. (2019) obtained pasta of lower sensory quality due to high bulkiness and adhesiveness with the use of MW-treated wheat. These authors suggested that MW treatment blocked gluten protein conformation through disulphide bond formation, limiting the availability of sulfhydryl groups, and preventing the formation of a strong network during pasta processing. M. Zhang et al. (2022) applied pregelatinized oat flour using MW to improve the extrusion process of oat noodles, achieving noodles of enhanced quality. MW treatment of whole wheat flour significantly improved the storage

Table 4
Effect of microwave treatment on *in vitro* protein digestibility of flour and protein samples.

Matrix	Treatment conditions	MW effect	Major findings	Reference
Wheat semolina	9 W/g; 1, 1.5, 2 min; natural MC; Domestic MW	Decrease	Reduced digestibility resulted from protein alteration, blocking active amino acid sites, forming crosslinks, and producing enzyme inhibitors, alongside Maillard derivatives inhibiting aminopeptidase through carbohydrate reactions under mild heat.	Kamble et al. (2020)
Sorghum flour	12.5 W/g; 15 min; 25 % MC; Industrial MW	Non-significant decrease	Enzymatically resistant protein polymers were formed by disulfide cross-linking of β and γ-kafirin, restricting protein digestion.	Baah et al. (2024)
Pigeon pea flour	3 min; 20 % w/v; Domestic MW	Increase	Increased random coil conformation and small particle size contributed to increased protein-protease interactions improving digestibility.	Sun et al. (2020)
Guar seed flour	1, 2 and 3 W/g; 3, 6 and 9 min; natural MC; Domestic MW	Increase	Inositol hexaphosphate breakdown into penta- and tetraphosphate, phytase inactivation, polar protein degradation, and improved hydrophobic interactions reduced anti-nutritional factors and enhanced *in vitro* protein digestibility.	Manikpuri et al. (2024)
Buckwheat protein	480, 720, 960 W; 1, 2, 3, 4, 5 min; 4 % w/v; Domestic MW	Increase	Microwave-induced structural modifications in proteins enhanced digestibility by causing disulfide bonds content loss, SH content increase, protein denaturation, transformation of β-turns into β-sheets and disordered coils, and alterations in microstructure and surface morphology. Despite microwaves increasing protein particle size, the aggregates likely formed due to electrostatic bonds, as indicated by the reduced magnitude of zeta potential.	Jin et al. (2022)
Quinoa protein	15 W/g; 70, 80 and 90 °C for 30 min; 20 % w/v; Laboratory MW	Increase*	Treatment at higher temperatures reduced digestion rates, probable because of protein aggregation and denaturation, which covered protease hydrolysis sites and hindered digestibility.	Cao et al. (2023)

The treatment conditions were as follows: power per gram of the sample (power only if data not provided), microwave exposure time, initial moisture content (MC) of the sample, and type of microwave equipment. MW effect: *in vitro* protein digestibility variation in treated samples in comparison with the native/untreated sample. *Compared to traditional thermal treatment.

stability of fresh noodles, largely by inhibiting microbial growth and inactivating polyphenol oxidase, in addition it enhanced dough stability and resistance to extension (Li et al., 2017). Enhancements in shelf life and quality were also reported for noodles prepared with MW-treated barley (Tuersuntuoheti et al., 2019). Liu et al. (2020) compared four thermal treatments of sorghum grains (MW, HMT, roasting, and stir-frying) in the characteristics and digestibility of 50:50 sorghum–-wheat noodles. HMT had the strongest impact, decreasing RDS and increasing RS through multi-scale starch rearrangements and the formation of a denser noodle microstructure. MW produced more modest effects, with lower structural modification. These differences may be attributed to the distinct conditions achieved by each treatment (moisture, temperature, and time). investigated the effect of MW treatment of green tea powder-wheat noodles. MW treatment of the dough (700 W, 30–45 s) enhanced the interaction between starch and tea polyphenols, as confirmed by water migration and structural analyses, leading to higher polyphenol stability and retention after boiling.

Modified starch, protein, or flour shows potential as a functional ingredient or filler in meat and plant-based meat replacing products, aligning with current industry trends. Chemically modified and pregelatinised starch have been commonly used these products (Bühler et al., 2022). Additionally, advanced processing techniques, such as shear, spinning, extrusion, and 3D printing, have been proposed to improve the texture of plant-based meat by enhancing protein–polysaccharide interactions (Tang et al., 2025). However, MW-treated starch, protein or flour has not yet been reported in this context, although some authors have suggested its potential as a thickener or texture enhancer.

6. Conclusions and prospects

The literature demonstrates that MW treatment of flours and grains significantly modifies their main biopolymers, namely, starch and protein. Starch modifications often include partial gelatinisation, rearrangement of amorphous and crystalline regions, and molecular breakage, while protein modifications often involve denaturation, aggregation, and changes in secondary and tertiary structures. These modifications influenced the functionality and digestibility of the treated flours, resulting in a wide range of functional ingredients that are suitable for use in product development. MW-treated flours have been

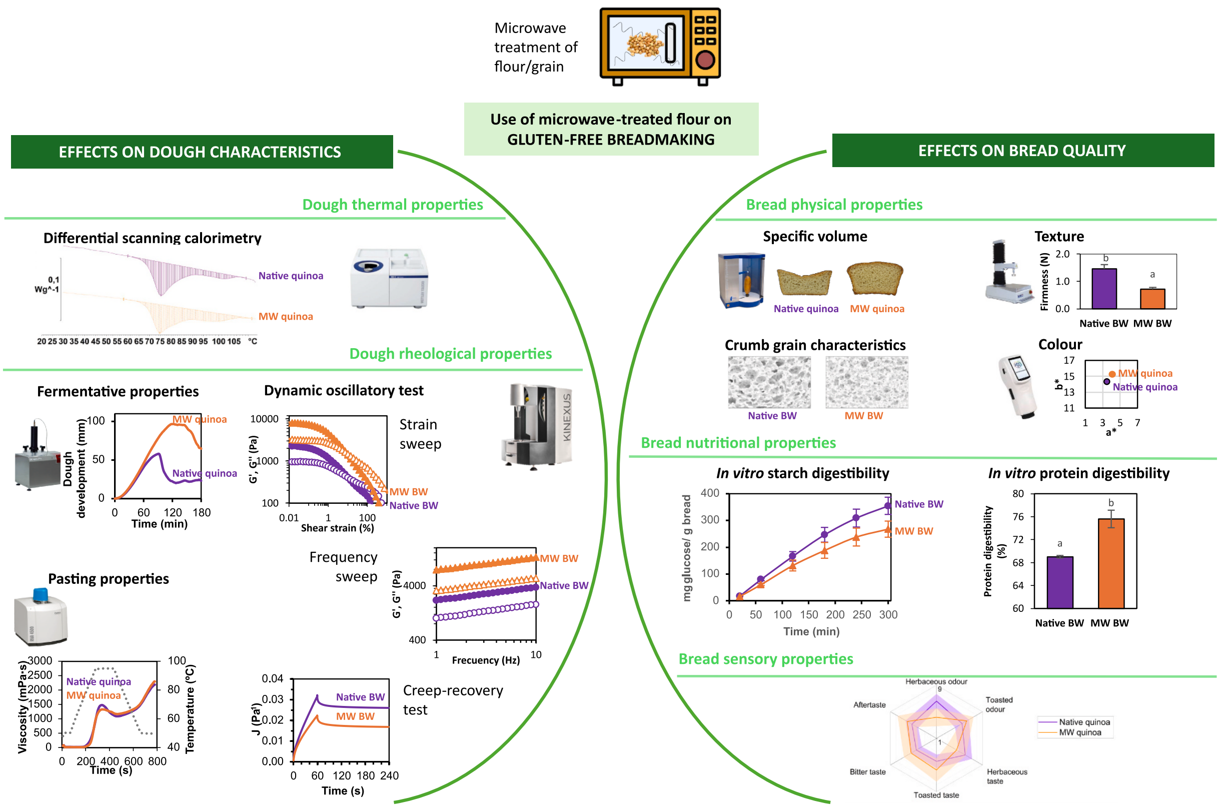

Fig. 3. Schematic representation of the effects of microwave-treated flour on the characteristics of gluten-free dough and the quality of the resulting bread. Data adapted from Vicente et al. (2024a)Vicente, Mauro, et al., 2025.

successfully utilised in various applications, including the production of gels with enhanced stability and viscoelasticity; gluten-free breads with better physical, nutritional, and/or sensory attributes; and porridges and rotis characterised by reduced rancidity and slower digestibility. These applications highlight the versatility and potential of MW technology to address challenges in food formulation, particularly in the development of innovative and health-oriented food products for populations with specific needs such as coeliacs.

The potential of MW technology for the physical modification of flours and grains has been clearly stated. However, significant research gaps remain in the establishment of more comprehensive relationships among biopolymer interactions (in particular starch and protein), food product structures, and their resulting properties. This will allow for better targeting and optimisation of MW modification outcomes for specific objectives. In this regard, the optimisation of treatment conditions to produce resistant starch is of great interest, maximizing, for example, its potential to enhance the complex formation of starch with lipids or polyphenols. Furthermore, future research should address research gaps in industrial scalability, including equipment design and process reproducibility. Most studies are performed on domestic or laboratory equipment and often fail to report the complete temperature–moisture evolution of the sample. The scarcity of this information, together with the limited number of studies directly using industrial MW systems, may limit the direct applicability of current findings and hinder the scalability of MW technology in food production.

CRediT authorship contribution statement

Ainhoa Vicente: Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Pedro A. Caballero:** Writing – review & editing, Supervision. **Marina Villanueva:** Writing – review & editing, Visualization. **Felicidad Ronda:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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