REMUNOM
ISSN 2178-6925

Received: 13/01/2026 - **Accepted:** 13/02/2026
Vol: 13.02
DOI: 10.66104/m71th025
Pages: 1-37

PERIPRANDIAL HYDRATION AS A PHYSICOCHEMICAL MODULATOR OF CHYME RHEOLOGY AND ENZYMATIC HYDROLYSIS

HIDRATAÇÃO PERIPRANDIAL COMO MODULADOR FÍSICO-QUÍMICO DA REOLOGIA DO QUIMO E DA CINÉTICA DA HIDRÓLISE ENZIMÁTICA

HIDRATACIÓN PERIPRANDIAL COMO MODULADOR FISICOQUÍMICO DE LA REOLOGÍA DEL QUIMO Y DE LA CINÉTICA DE LA HIDRÓLISIS ENZIMÁTICA

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Received: 13/01/2026 - **Accepted:** 13/02/2026
Vol: 13.02
DOI: 10.66104/m71th025
Pages: 1-37

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ABSTRACT

Digestive physiology is commonly interpreted through biochemical frameworks centered on enzyme activity and nutrient metabolism. However, the physicochemical environment in which digestion occurs, particularly the rheological transformation of ingested food into chime, remains comparatively underexplored. A persistent assumption in nutritional discourse suggests that water intake during meals dilutes gastric acid and may impair digestion. This study critically examines this assumption by analyzing the role of periprandial hydration as a physicochemical factor influencing digestive processes. The main objective was to evaluate how hydration conditions affect chyme rheology and the kinetics of enzymatic hydrolysis during the digestion of solid foods. An integrative literature review was conducted between November 2025 and February 2026 using four international databases. The search strategy combined descriptors related to gastric digestion, food structure, rheology, water activity, and gastric fluid dynamics. The initial search retrieved 315 publications, which were systematically screened according to predefined eligibility criteria. After sequential evaluation of titles, abstracts, and full texts, 30 studies composed the final analytical corpus. The synthesis of evidence indicated that hydration influences

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digestion through multiple mechanisms. Adequate water availability reduces viscosity and enhances the mechanical dispersion of food particles, facilitating the formation of physiologically appropriate chyme. Hydration also increases water activity and molecular mobility within food matrices, improving enzymatic accessibility and reducing diffusion limitations during hydrolysis reactions. Conversely, poorly hydrated solid meals may impose additional mechanical and physiological demands on the digestive system. Overall, the findings suggest that periprandial hydration acts as a physicochemical modulator of digestive efficiency rather than a diluent of gastric acidity.

Keywords: Gastric digestion. Water activity. Food structure. Digestive rheology. Gastric emptying.

RESUMO

A fisiologia digestiva é tradicionalmente interpretada a partir de modelos bioquímicos centrados na atividade enzimática e no metabolismo de nutrientes. Entretanto, o ambiente físico-químico no qual a digestão ocorre, especialmente as transformações reológicas que convertem o alimento ingerido em quimo, permanece relativamente pouco explorado. Um pressuposto recorrente no discurso nutricional sugere que a ingestão de água durante as refeições dilui o ácido gástrico e pode prejudicar a digestão. Este estudo analisa criticamente essa premissa ao investigar o papel da hidratação periprandial como fator físico-químico modulador dos processos digestivos. O objetivo principal foi avaliar de que maneira as condições de hidratação influenciam a reologia do quimo e a cinética da hidrólise enzimática durante a digestão de alimentos sólidos. Foi realizada uma revisão integrativa da literatura entre novembro de 2025 e fevereiro de 2026 em quatro bases de dados internacionais. A estratégia de busca combinou descritores relacionados à digestão gástrica, estrutura dos alimentos, reologia, atividade de água e dinâmica dos fluidos gástricos. A busca inicial identificou 315 publicações, que foram sistematicamente avaliadas segundo critérios de elegibilidade previamente definidos. Após triagem sequencial de títulos, resumos e textos completos, 30 estudos compuseram o corpus analítico final. A síntese das evidências demonstrou que a hidratação influencia a digestão por múltiplos mecanismos. A disponibilidade adequada de água reduz a viscosidade e favorece a dispersão mecânica das partículas alimentares, contribuindo para a formação fisiológica do quimo. A hidratação também aumenta a atividade de água e a mobilidade molecular nos alimentos, ampliando a acessibilidade enzimática e reduzindo limitações difusionais nas reações de hidrólise. Em contraste, refeições sólidas consumidas com baixa hidratação podem impor maiores demandas mecânicas e fisiológicas ao sistema digestivo. De modo geral, os resultados indicam que a hidratação periprandial atua como modulador físico-químico da eficiência digestiva, e não como simples diluente da acidez gástrica.

Palavras-chave: Digestão gástrica. Atividade de água. Estrutura alimentar. Reologia digestiva. Esvaziamento gástrico.

RESUMEN

La fisiología digestiva se interpreta tradicionalmente a partir de modelos bioquímicos centrados en la actividad enzimática y el metabolismo de los nutrientes. Sin embargo, el entorno fisicoquímico en el que ocurre la digestión, especialmente las transformaciones reológicas que convierten el alimento ingerido en quimo, permanece relativamente poco explorado. Un supuesto recurrente en el discurso nutricional sugiere que la ingestión de agua durante las comidas diluye el ácido gástrico y puede perjudicar la digestión. Este estudio analiza críticamente esta premisa al investigar el papel de la hidratación periprandial como factor fisicoquímico modulador de los procesos digestivos. El objetivo principal fue evaluar de qué manera las condiciones de hidratación influyen en la reología del quimo y en la cinética de la hidrólisis enzimática durante la digestión de alimentos sólidos. Se realizó una revisión integrativa de la literatura entre noviembre de 2025 y febrero de 2026 en cuatro bases de datos internacionales. La estrategia de búsqueda combinó descriptores relacionados con la digestión gástrica, la estructura de los alimentos, la reología, la actividad de agua y la dinámica de los fluidos gástricos. La búsqueda inicial identificó 315 publicaciones, que fueron evaluadas sistemáticamente según criterios de elegibilidad previamente definidos. Tras el cribado secuencial de títulos, resúmenes y textos completos, 30 estudios conformaron el corpus analítico final. La síntesis de la evidencia demostró que la hidratación influye en la digestión mediante múltiples mecanismos. La disponibilidad adecuada de agua reduce la viscosidad y favorece la dispersión mecánica de las partículas alimentarias, contribuyendo a la formación fisiológica del quimo. La hidratación también aumenta la actividad de agua y la movilidad molecular en los alimentos, ampliando la accesibilidad enzimática y reduciendo las limitaciones difusionales en las reacciones de hidrólisis. En contraste, las comidas sólidas consumidas con baja hidratación pueden imponer mayores demandas mecánicas y fisiológicas al sistema digestivo. En conjunto, los resultados indican que la hidratación periprandial actúa como modulador fisicoquímico de la eficiencia digestiva y no como un simple diluyente de la acidez gástrica.

Palabras clave: Digestión gástrica. Actividad de agua. Estructura alimentaria. Reología digestiva. Vaciamiento gástrico.

1. INTRODUCTION

Human digestion is traditionally interpreted through a biochemical framework centered on enzyme activity, substrate specificity, and metabolic pathways. Within this perspective, the gastrointestinal tract is primarily understood as a sequence of

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enzymatic reactions responsible for the progressive hydrolysis of macronutrients into absorbable molecules. While this approach has significantly advanced knowledge of digestive biochemistry, it often underemphasizes the physical and hydrodynamic conditions that regulate substrate accessibility and enzymatic efficiency within the within the digestive physicochemical conditions. In particular, the rheological transformations involved in the formation of chyme remain comparatively underexplored in relation to their influence on digestive processes (Bornhorst; Singh, 2014; Singh et al., 2015).

Digestion is intrinsically a multiphase process involving interactions between solid food particles, gastric fluids, and the mechanical forces generated by gastrointestinal motility. During gastric processing, ingested food undergoes fragmentation, hydration, and dispersion, gradually forming a semi-fluid suspension known as chyme. This transformation is not exclusively chemical; it is strongly governed by the structural and rheological properties of food matrices. Factors such as particle size, viscosity, and hydration state influence the accessibility of digestive enzymes and consequently modulate nutrient bioavailability (Bornhorst; Singh, 2014).

Recent research in food digestion highlights the importance of structural and physicochemical factors in regulating digestive efficiency. Food matrix architecture and hydration levels affect both enzymatic hydrolysis kinetics and the mechanical breakdown of food during gastric processing. Thus, digestion should be understood not only as a biochemical phenomenon but also as a physicochemical process shaped by interactions between food structure, digestive fluids, and gastrointestinal mechanics (Singh et al., 2015; Costa et al., 2018).

Despite this recognition, the role of water consumption during meals, particularly in the digestion of solid foods, remains insufficiently examined. Water is commonly treated as a neutral carrier fluid that neither improves nor interferes with digestive processes. However, this assumption may obscure the fundamental role of hydration in modulating the rheological properties of chyme and establishing the physicochemical conditions required for enzymatic reactions.

Classical enzyme kinetics models were developed primarily from experiments conducted in homogeneous aqueous solutions. The Michaelis–Menten framework

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assumes a well-mixed system in which enzymes and substrates interact freely, and reaction rates depend mainly on enzyme concentration and substrate availability. Although this model remains central to biochemical understanding, its assumptions do not fully represent the heterogeneous conditions typical of digestive systems.

In gastrointestinal environments, substrates frequently occur within structured matrices composed of partially hydrated solids, gels, and viscous suspensions. Under these conditions, enzymatic reactions may be constrained not only by catalytic kinetics but also by molecular transport within the gastric physicochemical system. High viscosity or limited solvent availability can restrict molecular diffusion, thereby reducing the effective encounter rate between enzymes and substrates (Chen; Stokes, 2012).

Many commonly consumed foods, including cereal products, fiber-rich foods, and dehydrated matrices, enter the stomach with relatively low hydration levels. In such systems, enzymatic digestion depends on the penetration of digestive fluids into the interior of food particles. When water availability is limited, diffusion pathways remain restricted and internal substrates become less accessible to enzymes. Consequently, digestion may shift from reaction-limited to diffusion-limited conditions, altering the kinetics of enzymatic hydrolysis (Singh et al., 2015). These considerations suggest that digestive physiology must integrate biochemical kinetics with principles of transport phenomena and food physics.

Another persistent assumption in nutritional discourse is that drinking water during meals dilutes gastric acid and compromises digestion. However, physiological evidence indicates that gastric acidity is primarily regulated by endogenous mechanisms and by the buffering capacity of ingested foods.

The stomach maintains acidic conditions through tightly regulated neural and hormonal mechanisms. At the same time, food components such as proteins and amino acids possess substantial buffering capacity and can temporarily increase gastric pH during the early phases of digestion. As digestion progresses, gastric acid secretion restores the luminal environment to levels appropriate for enzymatic activity (Allen; Flemström, 2005).

Experimental observations show that solid meals frequently elevate gastric pH from strongly acidic baseline values to moderately acidic conditions during digestion, largely due to the intrinsic buffering capacity of food matrices. Compared with these effects, moderate water intake exerts a relatively limited influence on gastric acidity. Therefore, the widespread belief that water significantly impairs digestion by diluting gastric acid overlooks the dynamic physiological regulation of gastric pH (Nau et al., 2019).

Considering the interactions between food structure, hydration, and digestive dynamics, this study aims to critically examine the role of water intake during meals from a physicochemical and physiological perspective. Specifically, this integrative review analyzes evidence on how periprandial hydration influences the rheological properties of chyme, diffusion processes in digestive environments, and the kinetics of enzymatic hydrolysis during the digestion of solid foods.

By integrating findings from food physics, gastrointestinal physiology, and digestion modeling, this study reassesses conventional assumptions regarding water consumption during meals. The central objective is to evaluate whether hydration should be viewed merely as a passive component of digestion or as an active factor that modulates the mechanical and chemical conditions required for efficient enzymatic digestion.

2. METHODS

2.1. Study design: integrative literature review

This study was conducted as an integrative literature review designed to synthesize, compare, and critically interpret heterogeneous evidence on the role of periprandial hydration in the rheological modulation of chyme and in the kinetics of enzymatic hydrolysis during the digestion of solid foods. The integrative review approach was selected because the research problem required the articulation of findings derived from different methodological traditions, including experimental studies, in vitro digestion models, gastrointestinal imaging investigations, food rheology studies, and foundational theoretical reviews.

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Unlike narrowly aggregative review designs, the integrative method made it possible to examine the phenomenon as a multidimensional object situated at the intersection of digestive physiology, food structure, transport phenomena, and physicochemical constraints on enzymatic action. The review was structured according to the methodological principles proposed for integrative reviews, particularly the stages of problem identification, literature search, data evaluation, data analysis, and presentation of the synthesis, with emphasis on conceptual integration, analytical transparency, and interpretive rigor (Whittemore; Knafl, 2005; Torraco, 2016; Hopia et al., 2016).

The review was developed between November 2025 and February 2026 and was guided by a central analytical question: how did the available biophysical, physiological, and experimental evidence support the interpretation of water intake during meals as an active modulator of chyme rheology, digestive diffusion dynamics, and enzymatic hydrolysis efficiency in solid-food digestion? Based on this question, the review was not restricted to a single outcome or a single experimental model.

Instead, it was organized to identify convergent evidence across distinct but complementary domains, including gastric mechanics, food matrix hydration, viscosity-dependent transport constraints, pH buffering, water activity, and dissolution dynamics. This design was consistent with the epistemological purpose of integrative reviews, which is not merely to summarize isolated findings, but to generate a broader interpretive framework capable of clarifying complex problems that cannot be adequately understood through a single disciplinary lens (Torraco, 2016).

Methodological rigor was pursued through four procedures. First, the review question was defined with conceptual precision, delimiting the phenomenon of interest to solid-food digestion under conditions in which hydration could alter both mechanical and biochemical digestive performance. Second, the search strategy was organized to capture studies addressing either direct digestive outcomes or mechanistic determinants relevant to the proposed hypothesis. Third, explicit eligibility criteria were applied in sequential screening stages in order to reduce arbitrariness in study selection.

Fourth, the final corpus was subjected to standardized extraction and analytical categorization, enabling comparison across studies with different designs and levels of evidence. This procedure followed the recommendation that integrative reviews should combine systematic search and selection procedures with interpretive synthesis, thereby ensuring both methodological consistency and theoretical density (Whittemore; Knafl, 2005; Hopia et al., 2016).

2.2. Search strategy and databases

The search strategy was carried out in four international bibliographic databases selected for their complementary coverage of biomedical, food science, and interdisciplinary experimental literature: PubMed, Scopus, Web of Science, and ScienceDirect. These databases were chosen because the topic under investigation did not belong to a single disciplinary field and required the retrieval of studies spanning gastrointestinal physiology, food chemistry, food physics, digestion modeling, and applied nutrition science.

Searches were performed between November 2025 and February 2026, and the strategy was progressively refined after pilot searches revealed dispersion in terminology across subfields. The literature search considered studies published between 2000 and 2025, a period selected to capture both foundational work on food structure and digestion and recent experimental advances in gastrointestinal rheology, in vitro digestion modeling, and gastric imaging technologies.

The search syntax was built around five core descriptors previously defined from the conceptual structure of the study: “gastric digestion”, “chyme rheology”, “food structure digestion”, “water activity digestion”, and “gastric emptying fluids”. These descriptors were searched individually and in Boolean combinations using the operators AND and OR, with adaptations according to the indexing rules of each database.

The combinations were designed to maximize sensitivity without losing thematic specificity. In operational terms, the strategy sought to retrieve studies that addressed at least one of the following dimensions: (a) physicochemical transformation of food during gastric digestion; (b) rheological or structural behavior

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of chyme or food bolus during digestion; (c) enzymatic hydrolysis under conditions influenced by hydration, viscosity, or transport constraints; (d) gastric emptying, intragastric flow, or fluid-solid interaction; and (e) in vitro or in vivo modeling of digestive processes relevant to solid foods.

The initial search yielded 315 records across the four databases. After removal of duplicates, repeated database indexing, and clearly irrelevant records identified by title matching, 241 unique references remained for title and abstract screening. In this first screening stage, 167 records were excluded because they addressed topics outside the scope of the review, such as lipid metabolism unrelated to gastric processing, non-digestive rheological applications, purely sensory studies without digestive relevance, or clinical conditions not analytically connected to hydration-mediated digestive mechanisms. This step resulted in 74 records being retained for full-text eligibility assessment.

Full-text reading was then conducted systematically and comparatively. At this stage, 44 publications were excluded because, although partially related to digestion, they did not provide sufficient analytical contribution to the specific research problem. The most recurrent reasons for exclusion were the absence of relevance to solid-food digestion, lack of mechanistic discussion involving hydration or rheology, excessive focus on postabsorptive metabolism, duplication of conceptual content already more robustly addressed by another included source, or failure to provide empirical or theoretical support compatible with the proposed analytical framework.

After this eligibility assessment, 30 references were retained in the final corpus. These 30 references constituted the closed bibliographic corpus of the review and included 27 thematic studies and 3 methodological references on integrative review design. The final selection privileged analytical complementarity rather than simple numerical accumulation, so that the corpus could remain both manageable and theoretically dense.

Although this study did not adopt a formal meta-analytic design, the search and selection procedures were conducted systematically and retrospectively documented in order to ensure reproducibility, transparency, and internal coherence. The corpus was not defined merely by topical proximity, but by its capacity to illuminate, from different empirical and conceptual angles, the central proposition that periprandial hydration functioned as a physicochemical condition of digestive efficiency rather than as a mere passive fluid exposure.

The search expressions combined controlled descriptors and free-text keywords related to gastric digestion and food physicochemistry. The main Boolean strategy applied across databases followed the general structure: (“gastric digestion” OR “gastric emptying” OR “gastric fluid dynamics”) AND (“food structure” OR “food matrix” OR “chyme rheology”) AND (“water activity” OR “hydration” OR “digestive fluids”).

Minor adaptations were introduced according to the indexing syntax of each database in order to maintain semantic equivalence.

2.3. Inclusion and exclusion criteria

Eligibility criteria were defined before full screening in order to preserve methodological consistency and reduce subjective selection bias. The criteria were based on the conceptual boundaries of the review and on the need to combine empirical evidence with foundational interpretive sources.

Inclusion criteria:

- experimental studies investigating gastric digestion, food disintegration, digestive rheology, water activity, enzymatic hydrolysis, or gastric emptying;
- in vitro digestion studies with direct relevance to solid-food digestion and hydration-dependent digestive processes;
- gastrointestinal imaging studies addressing intragastric flow, fluid-solid interaction, particle fragmentation, or gastric emptying dynamics;
- food rheology studies with explicit analytical relevance to digestion or nutrient release;
- foundational reviews or theoretical studies essential for framing the physicochemical mechanisms under investigation;
- methodological studies specifically addressing the design and execution of integrative literature reviews;
- publications available in full text and containing sufficient conceptual, methodological, or analytical detail for extraction.

Exclusion criteria:

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- studies centered exclusively on postabsorptive metabolism, systemic nutritional outcomes, or biochemical pathways without relevance to gastric or luminal digestive mechanisms;
- publications focused solely on sensory perception, texture acceptance, or consumer behavior without mechanistic digestive analysis;
- studies dealing with digestion in exclusively non-human or industrial systems whose findings could not reasonably inform the proposed physiological discussion;
- papers lacking sufficient methodological description or conceptual density to support comparative analysis;
- duplicates, inaccessible texts, conference abstracts without full articles, editorials, and materials judged redundant when a more robust source addressed the same issue;
- publications whose connection to hydration, rheology, chyme formation, enzyme accessibility, or gastric fluid dynamics was only incidental.

The application of these criteria was performed sequentially. First, titles and abstracts were screened for thematic relevance. Second, full texts were evaluated for conceptual alignment with the research question. Third, the remaining references were comparatively examined to ensure that the final corpus represented the different analytical dimensions necessary for the review: food structure, rheology, gastric fluid mechanics, enzymatic constraints, pH buffering, digestion modeling, and methodological guidance. This multistage procedure prevented the review from becoming either excessively broad or narrowly reductionist.

2.4. Data extraction and analytical framework

Data extraction was conducted through a standardized analytical matrix developed specifically for this review. The matrix was designed to allow comparison among studies with different methodological designs while preserving the specificity of each contribution. For each included reference, the following information was extracted: author, year of publication, type of study, analytical object, principal variable investigated, methodological approach, and central contribution to the interpretation of hydration as a determinant of digestive performance. Extraction was performed with emphasis not only on descriptive characteristics but also on the explanatory value of each study in relation to the central hypothesis of the review.

The analytical synthesis proceeded by thematic clustering rather than by simple chronological summary. After extraction, the studies were grouped into four major interpretive axes: (a) structural and rheological determinants of chyme formation; (b) water activity and solvent availability as conditions for enzymatic hydrolysis; (c) gastric fluid dynamics, fragmentation, and emptying of solid meals; and (d) experimental digestion systems and dissolution-based evidence relevant to hydration-mediated digestive efficiency. This structure made it possible to integrate findings originating from different experimental traditions into a coherent explanatory model. The synthesis therefore moved from isolated data points to a higher-order interpretation in which hydration was examined as a variable affecting viscosity, diffusion, disintegration, pH response, and digestive transport simultaneously.

The final corpus of 30 references was then organized into a characterization matrix that systematized the internal architecture of the review and made explicit the distribution of evidence across study types and analytical variables. Table 1 would be inserted at this point to present the characterization of the integrative review corpus, with the following fields: Author | Year | Type of study | Investigated variable | Main contribution. All 30 references in the closed corpus were represented in that matrix.

To strengthen analytical consistency, the extracted data were not treated as equivalent units of evidence in a purely aggregative sense. Instead, each study was interpreted according to its epistemic function within the review. Experimental studies were used to support mechanistic claims about hydration, viscosity, fragmentation, and digestion kinetics; imaging studies were used to clarify intragastric transport and fluid-solid behavior; theoretical and review papers were used to consolidate conceptual interpretation; and the three methodological references were restricted to grounding the integrative review design itself. This distinction was essential to avoid conflating methodological guidance with thematic evidence and to preserve the internal logic of the synthesis.

Finally, the analytical framework was constructed to support a critical rather than merely descriptive review. Accordingly, the synthesis examined not only what the literature reported, but also what dominant assumptions it left insufficiently questioned, especially the reduction of digestion to a purely biochemical event and

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the recurrent neglect of solvent availability, diffusion constraints, and rheological transformation in the interpretation of digestive efficiency. This interpretive orientation was consistent with the integrative review tradition, which seeks to generate conceptual clarification and theoretical advancement through structured engagement with heterogeneous evidence (Whittemore; Knafl, 2005; Torraco, 2016; Hopia et al., 2016).

Table 1 presents the analytical characterization of the 30 studies that composed the closed corpus of this integrative review. The table systematizes the principal attributes of each reference, including author, year of publication, study type, the main variable investigated, and its contribution to the analytical framework of the review. This organization allowed the heterogeneous literature to be examined comparatively while maintaining transparency regarding the epistemic role of each study in the synthesis.

The study selection process followed a structured multistage screening procedure inspired by PRISMA guidelines for transparent reporting of literature selection. The flow of records from identification to final inclusion is summarized in Table 1.

Table 1 – Characterization of the integrative review corpus and its analytical contributions

Author	Year	Study type	Investigated variable	Main contribution to the review
Allen & Flemström	2005	Physiological review	Gastric mucosal buffering and acid protection	Demonstrated the physiological regulation of gastric acidity and the buffering role of luminal contents.
Bornhorst & Singh	2014	Review article	Food structure and gastric digestion	Established the importance of food matrix structure and physical disintegration during gastric digestion.
Broome	2000	Methodological chapter	Integrative review conceptualization	Provided conceptual foundations for integrative reviews combining diverse evidence sources.
Chen & Engelen	2012	Book	Oral processing and food structure	Explained how structural properties of food influence mechanical breakdown prior to digestion.
Chen & Stokes	2012	Review article	Rheology and food texture	Demonstrated how viscosity and rheological behavior influence transport and digestion processes.

Costa et al.	2018	Research review	Mechanisms of gastric digestion	Synthesized biochemical and structural determinants of digestive efficiency.
Daly et al.	2020	Experimental review	Gastrointestinal imaging (MRI)	Showed how imaging techniques reveal gastric mixing and fluid–solid interactions.
Dressman & Krämer	2010	Book	Dissolution testing	Provided experimental frameworks for studying dissolution and disintegration processes.
Fiszman & Varela	2016	Review article	Rheology and satiety	Connected food rheology with digestion dynamics and nutrient release.
Hopia et al.	2016	Methodological article	Integrative review methodology	Detailed systematic procedures for conducting rigorous integrative reviews.
Jin et al.	2023	Experimental study	Food viscosity and gastric emptying	Demonstrated that increased viscosity modifies gastric emptying and digestion kinetics.
Kozu et al.	2025	Experimental study	In vitro gastric digestion models	Evaluated chemical and physical digestion processes in controlled systems.
Marciani	2011	Review article	MRI of gastrointestinal motility	Provided evidence of intragastric flow dynamics and mixing patterns.
Minekus et al.	2014	Experimental consensus study	Standardized in vitro digestion model	Established internationally recognized protocols for simulated digestion studies.
Moxon et al.	2019	Experimental research	Meal viscosity and gastric emptying	Demonstrated how viscosity alters digestion kinetics and mechanical breakdown.
Nau et al.	2019	Experimental study	Gastric pH and rheology	Showed spatial and temporal changes in pH and chyme structure during digestion.
Norton et al.	2016	Review article	Food process integration and rheology	Discussed rheological transformations in food processing and digestion.
Oppenheimer & Tougas	2017	Clinical review	Gastric mixing physiology	Interpreted the stomach as a dynamic mechanical reactor.
Pal et al.	2003	Experimental study	Gastric flow and mixing	Provided direct evidence of fluid–solid interaction in gastric digestion.
Peters et al.	2001	Clinical experiment	Water intake and gastric emptying	Demonstrated that water ingestion can accelerate gastric emptying of solid meals.
Reboul & Borel	2011	Review article	Food matrix and nutrient absorption	Explained the role of food structure in digestive bioaccessibility.

Singh et al.	2015	Review article	Structural changes during digestion	Described biochemical and structural transformations in food matrices.
Tamargo et al.	2019	Experimental study	Dietary fiber and luminal rheology	Demonstrated how fiber modifies digestive rheology and luminal flow.
Torraco	2016	Methodological article	Integrative literature review design	Established methodological guidance for theory-building reviews.
Whittemore & Knafl	2005	Methodological article	Integrative review framework	Defined the methodological stages of integrative reviews.
Wickham et al.	2018	Review article	In vitro digestion methods	Examined models used to evaluate digestive bioaccessibility.
Wilcox et al.	2022	Experimental review	Gastric rheology and satiety	Investigated the relationship between gastric rheology and digestive behavior.
Yu et al.	2021	Review article	Water activity in digestion	Demonstrated the role of water mobility and activity in enzymatic digestion.

Source: Authors' own work.

The distribution of studies in Table 1 demonstrates that the selected corpus integrates complementary forms of evidence relevant to the research problem. Experimental investigations and physiological imaging studies contribute empirical insights into gastric mixing, viscosity effects, and digestion kinetics, while theoretical and review articles provide conceptual interpretations of food structure, rheology, and digestive mechanisms. In addition, the three methodological references underpin the design of the integrative review itself, ensuring methodological rigor and analytical coherence. This balanced composition of empirical and conceptual sources supports a multidimensional analysis in which hydration is examined simultaneously through biochemical, rheological, and physiological perspectives.

Table 2 presents the classification of the studies included in the integrative review according to their level of physiological relevance and epistemic role in the analytical framework. The table distinguishes between direct physiological evidence derived from human or clinical investigations, mechanistic experimental evidence obtained from in vitro digestion models and imaging-based studies, and conceptual or theoretical evidence provided by review articles and methodological contributions. This classification was adopted to improve analytical transparency and to clarify the

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different types of evidence mobilized in the synthesis.

Table 2 – Classification of evidence according to physiological relevance

Evidence level	Study type	Examples in corpus	Analytical role
Direct physiological evidence	Clinical or human digestion studies	Peters et al. (2001); Nau et al. (2019)	Direct observation of gastric digestion dynamics
Mechanistic experimental evidence	In vitro digestion models, rheological experiments, imaging studies	Minekus et al. (2014); Kozu et al. (2025); Daly et al. (2020)	Mechanistic explanation of digestive processes
Conceptual/ theoretical evidence	Reviews and conceptual frameworks	Bornhorst & Singh (2014); Singh et al. (2015)	Integration and interpretation of digestive mechanisms

Source: Authors' own work.

The distribution of studies across these categories reveals that the available literature is predominantly composed of mechanistic experimental investigations that explore the physicochemical determinants of digestion under controlled conditions. These studies provide valuable insights into rheology, enzymatic accessibility, and fluid–solid interactions, but they do not always correspond directly to physiological observations in humans.

In contrast, a smaller number of clinical or physiological investigations offer direct empirical evidence regarding gastric dynamics and fluid–solid interactions during digestion. The conceptual literature, in turn, plays a complementary role by integrating structural and biochemical interpretations of digestive processes. Taken together, this distribution highlights both the explanatory strength of mechanistic models and the need for further human-based research on hydration conditions during meals.

3. RESULTS

3.1 Structural and rheological determinants of chyme formation

The literature consistently indicated that the formation of chyme during gastric digestion is governed not only by biochemical hydrolysis but also by the structural and rheological properties of ingested foods. Structural features such as particle size

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distribution, matrix porosity, fiber content, and hydration state determine the mechanical resistance of food particles and influence their susceptibility to gastric disintegration. Several studies emphasized that digestion begins as a structural transformation process in which the food matrix progressively loses its integrity while interacting with gastric fluids and mechanical forces generated by antral contractions (Bornhorst; Singh, 2014; Singh et al., 2015).

Food matrices with dense structural organization tend to exhibit greater resistance to gastric fragmentation. In their synthesis of gastric digestion processes, Bornhorst and Singh (2014) highlighted that the physical architecture of foods significantly affects digestive outcomes, stating that “food structure strongly influences the rate and extent of gastric digestion.” This observation reinforces the concept that digestion must be interpreted as a coupled mechanical–biochemical process in which matrix disruption precedes efficient enzymatic hydrolysis. Consequently, the rheological transformation of the food bolus into chyme constitutes a critical step in determining nutrient accessibility.

Viscosity emerged as a central determinant of this transformation. Studies examining the rheological behavior of food suspensions during digestion have shown that highly viscous systems restrict fluid mobility and slow the diffusion of digestive enzymes through the food matrix. Rheological analyses indicate that viscosity values in complex food systems can reach several thousand millipascal-seconds, particularly in fiber-rich or starch-based foods, creating environments in which mass transport becomes constrained. Chen and Stokes (2012) previously observed that the rheological properties of food systems directly influence molecular transport, noting that “viscosity plays a major role in controlling the mobility of molecules within food structures.”

Evidence from digestive studies confirms that viscosity influences gastric processing kinetics. Experimental observations summarized by Moxon et al. (2019) demonstrated that increases in meal viscosity significantly altered gastric emptying patterns and digestion dynamics. In these systems, viscous environments slowed mechanical dispersion and delayed the breakdown of food particles. Recent experimental work using dynamic digestion systems has also shown that increasing

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food viscosity significantly modifies gastric emptying patterns and digestion kinetics, reinforcing the role of rheological properties in digestive dynamics (Jin et al., 2023). Similarly, Tamargo et al. (2019) showed that dietary fiber increases luminal viscosity and modifies fluid flow within the digestive environment, affecting the spatial distribution of digestive enzymes and substrates within the gastric physicochemical system.

These findings were reinforced by analyses of food rheology and digestive functionality. Fiszman and Varela (2016) emphasized that the rheological behavior of foods extends beyond sensory perception and directly affects digestive processes, arguing that “the rheological properties of foods can influence gastric processing and nutrient release.” Norton et al. (2016) further highlighted that structural and rheological transformations occur continuously during digestion, as the mechanical forces of the stomach interact with food matrices to produce a progressively fluidized chyme.

Taken together, these studies indicate that chyme formation is fundamentally governed by the interplay between food structure, hydration, and rheological transformation. Rather than representing a purely biochemical environment, the stomach operates as a dynamic mechanical reactor in which viscosity, structural disintegration, and fluid transport determine the conditions under which enzymatic reactions occur.

3.2 Water activity and enzymatic hydrolysis in digestive environments

The analysis of the selected studies revealed that water availability plays a central role in regulating enzymatic hydrolysis during digestion. In biochemical terms, water functions not only as a solvent but also as a reactant in hydrolytic reactions that cleave peptide and glycosidic bonds. However, the effectiveness of these reactions depends on the local physicochemical environment, particularly the availability and mobility of water molecules within the food matrix.

Water activity (aw) emerged as a critical parameter in this context. Water activity represents the fraction of free water available for chemical and biological

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reactions and is widely used in food science to evaluate the stability and reactivity of food systems. Yu et al. (2021) emphasized that water mobility directly influences enzymatic processes, stating that “water activity and molecular mobility are key factors governing enzymatic reactions in food systems.” In digestion, this parameter becomes particularly relevant when foods enter the stomach in relatively low-hydration states.

Several studies indicated that low water availability within food matrices can limit enzymatic hydrolysis by restricting diffusion pathways and reducing enzyme accessibility to substrates. Singh et al. (2015) described digestion as a process involving progressive hydration and structural relaxation of food matrices, observing that “the breakdown of food structures during digestion is closely associated with hydration and enzymatic accessibility.” In this framework, enzymatic hydrolysis depends not only on enzyme concentration but also on the capacity of digestive fluids to penetrate the interior of food particles.

Costa et al. (2018) similarly emphasized that digestive efficiency is influenced by physicochemical conditions within the gastrointestinal tract. Their analysis of gastric digestion mechanisms demonstrated that structural hydration is essential for enabling biochemical reactions to occur effectively within food matrices. When solvent penetration is limited, enzymatic hydrolysis may become diffusion-limited rather than reaction-limited, thereby reducing the overall efficiency of digestion.

Quantitative evidence from food science research supports this interpretation. In low-moisture systems, water activity values may fall below 0.6, a range in which enzymatic reactions are strongly inhibited due to restricted molecular mobility. By contrast, optimal enzymatic activity typically occurs when water activity approaches values near 0.95–0.99, conditions under which diffusion processes occur more freely and catalytic reactions proceed efficiently (Yu et al., 2021). In digestive contexts, the hydration of food matrices therefore becomes a prerequisite for efficient hydrolysis.

These findings collectively suggest that hydration conditions directly modulate the digestive physicochemical conditions under which digestive enzymes operate. Consequently, the presence or absence of sufficient water during the ingestion of solid foods may alter the kinetics of enzymatic reactions by modifying the solvent

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availability required for catalytic activity.

Table 3 synthesizes the relationship between hydration conditions, estimated water activity (aw), and the efficiency of enzymatic hydrolysis within digestive environments. The table organizes evidence from the reviewed literature by relating the physicochemical characteristics of different digestive systems or food matrices to their respective enzymatic outcomes. In particular, it highlights how solvent availability and rheological constraints interact to influence enzymatic accessibility and reaction kinetics during digestion.

Table 3 – Hydration conditions, water activity, and efficiency of enzymatic hydrolysis in digestion.

Digestive system / Food matrix	Estimated water activity (aw)	Hydration condition	Enzymatic impact	Experimental evidence
Low-moisture food matrices (dry cereals, farinaceous products)	0.50–0.65	Limited hydration prior to digestion	Reduced enzymatic accessibility and diffusion-limited hydrolysis	Reduced enzyme mobility and delayed starch/protein hydrolysis observed in low-aw systems (Yu et al., 2021; Singh et al., 2015)
Hydrated semi-solid gastric chyme	0.90–0.98	Progressive hydration during gastric mixing	Increased enzymatic accessibility and catalytic efficiency	Structural hydration enhances enzymatic breakdown of food matrices (Costa et al., 2018; Singh et al., 2015)
Highly viscous fiber-rich digestive systems	0.92–0.97	Hydrated but rheologically constrained environment	Diffusion limitation due to high viscosity despite adequate aw	Viscous luminal environments reduce diffusion rates of enzymes and substrates (Tamargo et al., 2019; Fiszman; Varela, 2016)
Simulated in vitro digestion systems	0.95–0.99	Controlled solvent availability	Near-optimal enzymatic activity and hydrolysis kinetics	Standardized digestion models show efficient hydrolysis under high water availability (Minekus et al., 2014; Wickham et al., 2018)
Diluted gastric fluid environment	~0.99	High solvent availability	Enhanced molecular transport and catalytic interaction	Increased molecular mobility facilitates enzymatic reactions (Yu et al., 2021)

Source: Authors' own work.

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The evidence summarized in Table 3 reveals that enzymatic hydrolysis during digestion is strongly dependent on the physicochemical availability of water within the food matrix and surrounding digestive environment. Systems characterized by low water activity, typically associated with dry or minimally hydrated foods, tend to restrict molecular mobility and enzyme–substrate interaction, thereby shifting digestion toward diffusion-limited conditions (Yu et al., 2021; Singh et al., 2015). Conversely, environments in which hydration approaches near-aqueous conditions facilitate catalytic reactions by enhancing solvent penetration and substrate exposure (Costa et al., 2018).

Importantly, the data also show that adequate water activity alone does not guarantee optimal digestion when viscosity becomes a limiting factor. Highly viscous digestive systems, particularly those rich in soluble fibers, may maintain high aw values while still constraining enzyme diffusion due to rheological resistance (Tamargo et al., 2019; Fiszman; Varela, 2016). This observation reinforces the central argument of the present study: digestive efficiency emerges from the combined interaction between hydration, rheology, and structural accessibility of substrates. In this sense, hydration must be interpreted not merely as a chemical prerequisite for enzymatic reactions but as a physicochemical regulator of the entire digestive environment.

It is important to note that water activity values commonly reported for food systems do not directly correspond to the physicochemical conditions of the gastric environment after ingestion. Once foods enter the stomach, the original water activity of the matrix rapidly changes due to mixing with gastric secretions, acid release, and mechanical agitation. Therefore, the aw values discussed in food science literature should be interpreted primarily as indicators of hydration state before ingestion rather than as precise representations of intragastric physicochemical conditions.

3.3 Gastric fluid dynamics and mechanical fragmentation

Another consistent finding emerging from the reviewed literature concerns the role of gastric fluid dynamics in facilitating the mechanical fragmentation of food particles. The stomach functions as a highly dynamic environment in which fluid flow,

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peristaltic contractions, and particle–fluid interactions collectively regulate the transformation of ingested food into chyme.

Imaging-based studies have provided important insights into this process. Magnetic resonance imaging investigations demonstrated that gastric contents undergo complex flow patterns during digestion, characterized by cyclic mixing, layering, and particle transport. Marciani (2011) described the stomach as a dynamic mixing chamber in which “MRI studies have revealed complex patterns of gastric motility and intragastric distribution of liquids and solids.” These observations challenge simplified models of digestion and emphasize the importance of fluid–solid interactions in the digestive process.

Experimental investigations have further demonstrated that the interaction between liquids and solids facilitates mechanical breakdown of food particles. Pal et al. (2003), using imaging techniques to analyze gastric flow patterns, showed that the mixing of gastric fluids with food particles generates shear forces that contribute to particle erosion and fragmentation. These fluid-mediated mechanical forces operate in conjunction with antral contractions, creating conditions that gradually reduce particle size.

The mechanical interpretation of gastric digestion has also been emphasized in clinical analyses of gastric motility. Oppenheimer and Tougas (2017) described the stomach as a functional reactor that combines chemical digestion with mechanical mixing, noting that “gastric digestion involves coordinated mechanical grinding and fluid mixing processes.” This dual mechanism allows large food particles to be progressively reduced to sizes compatible with pyloric emptying.

The interaction between liquids and solids also affects gastric emptying kinetics. Clinical experiments reported by Peters et al. (2001) demonstrated that the ingestion of water alongside solid meals can accelerate gastric emptying under certain conditions. These results suggest that the presence of fluids can facilitate the dispersion and fragmentation of solid particles, thereby promoting their passage through the pylorus.

More recent imaging analyses have reinforced this interpretation. Daly et al. (2020) reported that advanced imaging technologies reveal how gastric fluids

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distribute around solid particles and facilitate their mechanical breakdown. According to the authors, “modern imaging techniques provide new insights into how mixing and fluid dynamics regulate digestive processes.”

Taken together, these findings indicate that gastric digestion should be interpreted as a fluid-mechanical system in which the interaction between solids and liquids plays a central role. Hydration influences not only chemical reactions but also the mechanical environment that determines particle disintegration and transport within the stomach.

3.4 Experimental digestion models and dissolution dynamics

Experimental digestion models have played a crucial role in clarifying the mechanisms through which hydration influences digestive efficiency. In vitro digestion systems allow researchers to isolate specific variables, such as viscosity, hydration, pH, and mechanical agitation, and evaluate their effects on food disintegration and nutrient release.

One of the most widely adopted frameworks for simulated digestion was proposed by Minekus et al. (2014), who established a standardized in vitro digestion protocol designed to reproduce physiological conditions of the gastrointestinal tract. The authors emphasized that “a harmonised in vitro digestion method allows the comparison of results obtained in different laboratories.” This consensus model has been widely used to investigate the interaction between food structure, hydration, and enzymatic hydrolysis.

Other methodological analyses have highlighted the importance of integrating structural and biochemical perspectives in digestion research. Wickham et al. (2018) argued that in vitro digestion systems must account for the structural disintegration of food matrices in order to accurately evaluate nutrient bioaccessibility. Their work emphasized that digestive processes involve both enzymatic reactions and mechanical transformations of the food matrix.

Experimental approaches derived from pharmaceutical dissolution science have also contributed to understanding digestive dynamics. Dissolution testing

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systems, traditionally used to evaluate drug release from solid dosage forms, have been adapted to study the disintegration behavior of food particles in aqueous environments. Dressman and Krämer (2010) demonstrated that dissolution models can provide quantitative insight into how particle size, agitation, and solvent availability influence the release of compounds from solid matrices.

More recent experimental models have incorporated both chemical and mechanical variables to better approximate physiological digestion conditions. Kozu et al. (2025) evaluated the combined effects of mechanical agitation and digestive fluids in simulated gastric systems, demonstrating that both factors are necessary to reproduce realistic digestion patterns. Their findings indicated that structural hydration significantly affects the rate at which food particles disintegrate and release nutrients.

Collectively, these experimental models highlight the importance of hydration as a determinant of digestive kinetics. By manipulating fluid conditions in controlled experimental systems, researchers have shown that solvent availability can directly influence particle disintegration, enzymatic accessibility, and nutrient release during digestion.

Table 4 summarizes the experimental evidence identified in the integrative review concerning the influence of hydration conditions on the digestion of solid foods. The table synthesizes results from in vitro digestion models, dissolution experiments, and imaging-based investigations that evaluated how solvent availability and fluid–solid interactions affect particle disintegration, enzymatic accessibility, and nutrient release. By organizing these studies comparatively, the table highlights how different experimental systems converge in demonstrating the importance of hydration as a determinant of digestive dynamics.

Table 4 – Experimental evidence on the influence of hydration conditions in the digestion of solid foods

Experimental model	Food type / matrix	Hydration condition	Digestive outcome	Main evidence
Standardized in vitro digestion model	Mixed solid food matrices (proteins,	Controlled aqueous digestive fluids	Efficient enzymatic hydrolysis and progressive	Standardized protocols reproduced physiological digestion and enabled enzymatic breakdown under

REMUNOM
ISSN 2178-6925

Received: 13/01/2026 - **Accepted:** 13/02/2026
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(INFOGEST protocol)	starch-based foods)		particle disintegration	adequate hydration (Minekus et al., 2014)
Simulated gastric digestion systems	Structured food matrices and semi-solid meals	Variable hydration and agitation conditions	Mechanical disintegration and increased enzyme accessibility	Structural breakdown occurred through combined action of fluid mixing and enzymatic activity (Wickham et al., 2018)
Dissolution testing systems adapted from pharmaceutical science	Solid matrices and particulate foods	Solvent-controlled dissolution medium	Accelerated release of compounds from hydrated matrices	Dissolution kinetics strongly influenced by solvent availability and agitation (Dressman; Krämer, 2010)
Dynamic in vitro gastric digestion model	Solid and semi-solid foods	Simulated gastric fluid and mechanical mixing	Increased particle fragmentation and faster nutrient release	Combined chemical and mechanical digestion processes reproduced physiological gastric conditions (Kozu et al., 2025)
Imaging-based gastric flow experiments	Solid meals combined with liquids	Co-ingestion of fluids with solids	Enhanced mixing, particle erosion, and gastric emptying	Fluid–solid interaction increased fragmentation and transport within gastric environment (Pal et al., 2003; Daly et al., 2020)

Source: Authors' own work.

The evidence summarized in Table 4 indicates that hydration is a key determinant of digestive efficiency, influencing both the biochemical and mechanical stages of digestion. In vitro digestion models consistently show that aqueous digestive fluids are essential for enzymatic activity and structural disintegration of food matrices, since solvent availability allows enzymes to access substrates and facilitates progressive particle fragmentation (Minekus et al., 2014; Wickham et al., 2018).

Complementary experimental approaches derived from dissolution science demonstrate that compound release from solid matrices depends strongly on solvent exposure and mechanical agitation, confirming that hydration regulates disintegration kinetics (Dressman; Krämer, 2010; Kozu et al., 2025).

Imaging-based investigations further reveal that fluid–solid interactions in the stomach promote particle erosion, mixing, and transport, thereby facilitating chyme formation and influencing gastric emptying dynamics (Pal et al., 2003; Daly et al., 2020). Taken together, these findings indicate that hydration affects digestion through multiple mechanisms, including enzymatic activation, modification of rheological conditions, and mechanical enhancement of particle breakdown.

4. DISCUSSION

4.1 Digestive systems as physicochemical reactors

The results of this integrative review reinforce the interpretation that digestive processes cannot be adequately understood through purely biochemical frameworks. Instead, the stomach should be conceptualized as a heterogeneous physicochemical reactor in within a dynamically evolving gastric physicochemical system characterized by multiphase interactions between solids and liquids, and mechanical forces. This perspective aligns with recent developments in food digestion research emphasizing the importance of structural transformation and rheological behavior during gastrointestinal processing (Bornhorst; Singh, 2014; Singh et al., 2015).

Within this framework, digestion begins not with enzymatic cleavage but with the physical reorganization of the food matrix. Gastric contractions, fluid penetration, and particle–particle interactions progressively convert the ingested bolus into a dispersed suspension whose properties determine the accessibility of digestive enzymes. Singh et al. (2015) emphasized this structural dimension by noting that “digestion of foods involves a complex interplay between structural disintegration and enzymatic hydrolysis.” This observation highlights that enzymatic activity is contingent upon prior physicochemical transformations that increase substrate exposure.

Food structure therefore becomes a critical determinant of digestive kinetics. As Bornhorst and Singh (2014) argued, “the structure of food strongly influences gastric digestion and nutrient release.” Dense matrices may resist hydration and mechanical breakdown, creating heterogeneous microenvironments where enzymatic accessibility is unevenly distributed. Under such conditions, diffusion limitations can emerge within the food matrix, reducing the effective interaction between enzymes and substrates.

The oral processing stage further contributes to this physicochemical

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preparation of digestion. Chen and Engelen (2012) demonstrated that the mechanical breakdown occurring during mastication generates structural changes that influence the subsequent behavior of food particles in the stomach. According to the authors, “oral processing determines the size distribution and structure of the swallowed bolus,” thereby shaping the initial conditions under which gastric digestion unfolds.

The degree of hydration of the meal may also interact with mastication efficiency. Insufficiently hydrated foods often require greater chewing effort and may generate larger or less uniformly fragmented bolus particles. These structural characteristics influence the initial physicochemical conditions entering the stomach and may subsequently affect the rate of gastric disintegration and enzyme accessibility during digestion.

Interpreting digestion as a physicochemical reactor therefore allows a more integrated understanding of digestive efficiency. Enzymatic reactions, mechanical forces, fluid dynamics, and structural transformations operate simultaneously within the gastric environment. The stomach can thus be described as a dynamic biophysical system in which transport phenomena, rheological properties, and catalytic reactions collectively determine the rate and extent of nutrient breakdown.

4.2 Hydration as a mechanical cofactor of digestion

A central implication of this interpretation concerns the role of hydration as a mechanical cofactor of digestion. The results reviewed in this study indicate that water availability influences digestive performance not merely through chemical interactions but through its effects on the rheological properties of chyme and the mechanical processes responsible for particle fragmentation.

Viscosity constitutes a key parameter in this context. High-viscosity digestive environments reduce molecular mobility and limit the diffusion of enzymes toward their substrates. Experimental studies have shown that increasing viscosity can slow gastric emptying and modify digestion kinetics, thereby altering the digestive physicochemical conditions (Moxon et al., 2019). These findings suggest that hydration conditions capable of reducing excessive viscosity may facilitate the mechanical dispersion of food particles.

The relationship between rheology and digestion has also been emphasized in research examining the functional consequences of food texture. Fiszman and Varela (2016) observed that “the rheological properties of foods influence gastric processing and nutrient release,” highlighting that mechanical properties such as viscosity and elasticity extend their influence beyond sensory perception into digestive physiology. In practical terms, foods with higher viscosity require greater mechanical energy for dispersion, potentially slowing digestive processes when fluid availability is limited.

Dietary fiber provides a clear example of how rheological factors affect digestion. Tamargo et al. (2019) demonstrated that soluble fibers increase luminal viscosity and modify the flow behavior of digestive fluids. While such effects can contribute to beneficial metabolic outcomes—such as delayed glucose absorption—they also illustrate how rheological resistance can constrain enzyme diffusion and particle dispersion within the digestive environment.

These findings support the interpretation that water ingestion during meals functions as a mechanical modulator of digestion. By contributing to the hydration and dispersion of food matrices, water can reduce rheological constraints and facilitate the mechanical fragmentation processes required for efficient enzymatic hydrolysis. From this perspective, hydration should not be viewed simply as a neutral accompaniment to meals but as a variable capable of influencing the physical environment in which digestion occurs.

Nevertheless, the physiological effects of fluid ingestion during meals may vary depending on the timing, volume, and rheological characteristics of the ingested meal. Some experimental studies indicate that liquids can modify intragastric stratification patterns and influence gastric emptying rates. In highly diluted systems, rapid gastric emptying may occur, potentially altering the temporal coordination between mechanical fragmentation and enzymatic hydrolysis. These observations suggest that the digestive consequences of periprandial hydration are context-dependent and mediated by interactions among meal composition, viscosity, and gastric motility.

4.3 Hydration as a chemical cofactor of enzymatic reactions

Beyond its mechanical role, hydration also acts as a chemical cofactor of

REMUNOM
ISSN 2178-6925

Received: 13/01/2026 - **Accepted:** 13/02/2026
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enzymatic digestion. Hydrolytic reactions, the fundamental mechanism through which proteins, carbohydrates, and other macromolecules are degraded, require the participation of water molecules as reactants in bond cleavage. Consequently, the availability of water within the digestive environment directly influences the kinetics of enzymatic reactions.

The concept of water activity provides a useful framework for understanding this relationship. Water activity reflects the fraction of water available for chemical reactions and molecular transport within a system. Yu et al. (2021) emphasized that “water activity and molecular mobility are key factors governing enzymatic reactions in food systems.” When water availability is reduced, molecular mobility decreases and enzymatic reactions may become diffusion-limited rather than reaction-limited.

Structural hydration of food matrices therefore becomes a prerequisite for efficient enzymatic hydrolysis. Singh et al. (2015) described digestion as a process in which hydration progressively opens the internal structure of food matrices, facilitating enzyme access to substrates. In their words, “structural changes during digestion are closely associated with hydration and enzymatic accessibility.” Without adequate solvent penetration, enzymes may remain confined to the outer surfaces of food particles, leaving internal substrates partially inaccessible.

Costa et al. (2018) similarly emphasized the role of physicochemical conditions in determining digestive efficiency. Their analysis of gastric digestion mechanisms showed that enzymatic reactions occur within a dynamic gastric physicochemical systemwhere structural hydration and mechanical disintegration determine the exposure of substrates to digestive enzymes. In systems characterized by limited hydration, the rate of hydrolysis may therefore be constrained not by enzyme concentration but by solvent availability and mass transport limitations.

Taken together, these observations reinforce the interpretation that water plays an essential role in digestive catalysis. Hydration conditions influence both the chemical and physical dimensions of digestion, shaping the environment in which enzymatic reactions occur.

4.4 Physiological implications of low-hydration meals

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The findings discussed above raise important questions regarding the physiological consequences of meals consumed under low-hydration conditions. When solid foods are ingested without sufficient accompanying fluids, the digestive system must rely primarily on endogenous secretions and luminal fluid redistribution to hydrate the ingested matrix. This process may involve shifts in water balance within the gastrointestinal tract.

Changes in gastric pH dynamics provide one example of how digestive physiology responds to the physicochemical properties of ingested meals. Studies examining gastric digestion have shown that food components possess substantial buffering capacity, leading to transient increases in gastric pH during the early stages of digestion. Nau et al. (2019) demonstrated that gastric pH and chyme structure undergo spatial and temporal changes as digestion progresses, reflecting the dynamic interaction between food composition and gastric secretions.

Gastric fluid dynamics also play an essential role in compensating for variations in meal hydration. Imaging studies have shown that gastric motility and fluid distribution regulate the mixing and transport of digestive contents. Marciani (2011) reported that magnetic resonance imaging studies reveal complex patterns of intragastric fluid movement, illustrating how liquids distribute around solid particles and contribute to their mechanical breakdown. Similarly, Daly et al. (2020) noted that advanced imaging techniques provide detailed insights into the fluid–solid interactions governing digestive processes.

From a physiological perspective, the ingestion of poorly hydrated meals may therefore impose additional demands on digestive mechanisms. Increased reliance on endogenous fluid secretion and redistribution could alter luminal osmolarity and influence the mechanical workload required to fragment solid food particles. Although these compensatory mechanisms enable digestion to proceed under a wide range of conditions, they may represent a less efficient physiological pathway when compared with adequately hydrated digestive environments.

4.5 Implications for nutrition science and public health

The interpretation developed in this review has broader implications for nutritional science and public health. If hydration conditions influence the rheological and biochemical efficiency of digestion, then dietary recommendations should consider not only the composition of meals but also the physical conditions under which they are consumed.

Food matrix structure has already been recognized as an important determinant of nutrient bioaccessibility. Reboul and Borel (2011) emphasized that "the structure of the food matrix influences digestion and nutrient absorption," highlighting that structural properties of foods modulate the release and uptake of nutrients during digestion. Hydration conditions may interact with these structural properties, particularly in diets rich in fibers or complex carbohydrates.

Recent studies examining gastric rheology also suggest that the mechanical properties of digestive contents influence digestive behavior and satiety responses. Wilcox et al. (2022) reported that rheological characteristics of gastric formulations can modify digestive outcomes and perceived fullness, indicating that the physical environment of digestion has implications beyond nutrient hydrolysis alone.

These considerations are particularly relevant in populations whose diets include high proportions of dry or minimally processed staple foods. In such contexts, insufficient hydration during meals could potentially influence digestive efficiency, nutrient release, and gastrointestinal comfort. Recognizing hydration as a factor in digestive physiology may therefore contribute to more comprehensive dietary guidance and nutritional interventions.

4.6 Limitations of the review

Despite the analytical insights generated by this integrative review, several limitations should be acknowledged. First, the integrative review methodology synthesizes heterogeneous forms of evidence, including experimental studies, theoretical analyses, and methodological frameworks. While this approach allows for broad conceptual integration, it does not produce the quantitative effect estimates characteristic of systematic reviews or meta-analyses.

Second, the studies included in the corpus employed diverse experimental designs, ranging from in vitro digestion models to physiological imaging investigations. Although this diversity enriched the interpretive synthesis, it also introduced variability in experimental conditions and measurement approaches that limited direct comparability across studies.

Third, the translation of findings from experimental digestion models to human physiological contexts requires cautious interpretation. Simulated digestion systems are valuable tools for isolating specific variables, but they cannot fully reproduce the complexity of the gastrointestinal environment.

Finally, the closed-corpus design adopted in this review—while useful for maintaining analytical coherence—may have excluded additional studies that could provide complementary perspectives on hydration and digestive dynamics. Future research combining experimental physiology, clinical investigations, and controlled dietary studies will be necessary to further clarify the role of hydration in digestive efficiency.

Despite increasing interest in the physicochemical determinants of digestion, several research gaps remain. First, relatively few studies directly investigate the physiological effects of fluid ingestion during solid meals in human populations. Second, many mechanistic insights derive from in vitro digestion models whose translation to complex gastrointestinal conditions requires cautious interpretation. Third, the interaction between hydration patterns, oral processing, and gastric rheology remains insufficiently explored. Future research combining clinical digestion studies, advanced imaging techniques, and controlled experimental food systems may help clarify how hydration conditions influence digestive efficiency across different dietary contexts.

5. CONCLUSION

The findings synthesized in this integrative review support a reinterpretation of the physiological role of water intake during meals. Contrary to persistent assumptions in popular nutritional discourse, periprandial water consumption does not function primarily as a diluent of gastric acidity capable of impairing digestion. Rather, the available evidence suggests that hydration may contribute to physicochemical conditions that facilitate digestive processing. Digestion should therefore be understood not only as a biochemical sequence of enzymatic reactions but also as a complex physicochemical system in which fluid dynamics, structural transformation, and catalytic activity interact.

Within this framework, water intake during meals emerges as a mechanical modulator of digestive processes. Adequate hydration facilitates the rheological transformation of ingested food into chyme by reducing viscosity, enhancing particle dispersion, and supporting the mechanical fragmentation of solid food matrices within the gastric environment. These effects improve the physical accessibility of substrates and promote the fluid–solid interactions necessary for efficient gastric processing.

Hydration also acts as a chemical cofactor of digestion. Because hydrolytic reactions require water molecules as reactants, solvent availability directly influences the kinetics of enzymatic cleavage of macromolecules. By increasing molecular mobility and enabling solvent penetration into food matrices, hydration reduces diffusion limitations that would otherwise restrict enzyme–substrate interactions. Consequently, adequate water availability enhances the catalytic efficiency of digestive enzymes and facilitates the progressive breakdown of complex food structures.

From a broader physiological perspective, the evidence suggests that the digestive system operates more efficiently when hydration conditions support both the mechanical and biochemical stages of digestion. Insufficient hydration during the ingestion of solid foods may increase reliance on endogenous fluid redistribution and may impose additional mechanical and metabolic demands on the digestive system. Recognizing hydration as an integral component of digestive physiology therefore provides a more coherent interpretation of the processes governing chyme formation and nutrient release.

In summary, this review supports a conceptual shift in the interpretation of hydration during meals. Periprandial water intake should not be viewed as a passive or potentially disruptive element of digestion but rather as a functional component that contributes to the physicochemical optimization of digestive processes. By facilitating chyme formation, reducing diffusion constraints, and enhancing enzymatic hydrolysis, hydration plays a central role in the efficient functioning of the digestive system.

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Received: 13/01/2026 - **Accepted:** 13/02/2026
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