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Starch-based hydrogels: current status and applications in food

Hidrogéis à base de amido: status atual e aplicações em alimentos

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ABSTRACT

Hydrogel is a gel formed by a three-dimensional network of hydrophilic polymers and copolymers, widely used for different purposes in the textile, pharmaceutical, cosmetic, biomedical, and food industries. The use of starch hydrogels in food applications is growing and can be used mainly as a release control system for bioactive compounds, ingredient for 3D printing of food and in bioactive films. This integrative review aimed to bring the current scenario of the development of starch-based hydrogels and their use in the food area. Studies published from 2011 to 2021, available in full, published in Portuguese, English or Spanish, were selected. 631 studies were found in the searched databases. Of these, 599 were excluded and 32 selected. Studies have revealed that the development of starch hydrogels has increased more and more, being widely discussed nowadays, with relevance for application in the food area.

Keywords: biopolymer, food gels, technological applications.

RESUMO

O hidrogel é um gel formado por uma rede tridimensional de polímeros e copolímeros hidrofílicos, amplamente utilizado para diferentes fins nos setores têxtil, farmacêutico, cosmético, biomédico e alimentício. O uso de hidrogéis de amido em aplicações alimentícias está crescendo e pode ser usado principalmente como um sistema de controle de liberação de compostos bioativos, ingrediente para impressão 3D de alimentos e em filmes bioativos. Esta revisão integrativa teve como objetivo trazer o cenário atual do desenvolvimento de hidrogéis à base de amido e seu uso na área de alimentos. Foram selecionados estudos publicados de 2011 a 2021, disponíveis na íntegra, publicados em português, inglês ou espanhol. Foram encontrados 631 estudos nas bases de dados pesquisadas. Desses, 599 foram excluídos e 32 selecionados. Os estudos revelaram que o desenvolvimento de hidrogéis de amido tem aumentado cada vez mais, sendo amplamente discutido na atualidade, com relevância para aplicação na área de alimentos.

Palavras-chave: biopolímero, géis alimentícios, aplicações tecnológicas.

1 INTRODUCTION

Hydrogels are networks of crosslinked polymers with high hygroscopic properties. Its formation occurs from physically or chemically cross-linked macromolecules, giving rise to a three-dimensional network with a high capacity to retain water molecules or other biological fluids, without its disintegration, thus forming strong and stable interconnected structures, due to physical interactions or through the covalent bonds formed (Ismail et al., 2013; Koev et al., 2020; Larrea-Wachtendorff et al., 2020).

In hydrogels, the network is formed by the simple reaction of one or more polymers, which are cross-linked by different mechanisms, such as covalent and hydrogen bonds, van der Waals forces or just physical interactions. Thus, hydrogels can contain a large amount of water within their structure due to the presence of hydrophilic groups in the structuring agents (such as –OH, –CONH–, –CONH2, –COOH and –SO3H) (Ahmed, 2015; Flory, 1953; Kamath and Park, 1993). Hydrogels can be produced based on synthetic polymers (poly(vinyl alcohol) (PVA); polymethyl methacrylate (acrylic); polystyrene; polyvinyl chloride (PVC); polyethylene and polypropylene), natural (starch; cellulose; chitosan; gum xanthan; pectin) or a mixture of the two. Its application depends on the definition of the polymer used, according to its properties. The preparation of hydrogels based on synthetic polymers has a great disadvantage, as they are generally derived from petroleum and have low degradability and non-regenerability (Xiao, 2013).

In recent years, interest in developing hydrogels based on natural polymers has increased considerably among researchers and industry, as these materials are biodegradable, leading to their sustainable development, with minimal ecological impacts. In addition, the molecular chains of natural polymers distribute hydrophilic groups (such as hydroxyl groups), improving the hydrophilic and biocompatibility properties, which makes these hydrogels promising for various applications. Among biopolymers, starch-based polymers took an important step towards the development of hydrogels (Niranjana-Prabhu and Prashantha, 2018; Zhu et al., 2015).

Recently, alternative methods for the formation of hydrogels have been widely studied in order to respond to the growing demand for ecologically sustainable processes, such as starch oxidation by ozone, physical modification of starch by dry heating treatment (DHT), and by high speed shear homogenizer (Koev et al., 2020; Lima et al., 2020; Maniglia et al., 2020; Tangsrianugul et al., 2015). These methods surpass the conventional ones in their main limitations, such as long process duration and high cost (Larrea-Wachtendorff et al., 2020).

Hydrogels are promising candidates for various technological applications, due to their complex and heterogeneous structure and organization (Koev et al., 2020). Hydrophilic gels for biological use were first reported in 1960 (Wichterle and Lin, 1960).

Since then, hydrogels have been widely studied and applied, with different purposes, such as disposable diapers, soil additives in agriculture, biosensors (Park et al., 2012), heavy metal adsorbents (Zhu et al., 2015), controlled release of antimicrobial drugs or proteins (Zhang et al., 2011), three-dimensional structures for cell adhesion and proliferation, tissue engineering and regenerative medicine (Hu et al., 2019), in paper, textile, plastic, cosmetic, adhesive, and pharmaceutical industries (Li et al., 2017).

Starch is a material of interest to be used in the production of hydrogels due to its low cost and biocompatibility (Koev et al., 2020). As it is widely accessible, renewable and biodegradable, in addition to its physicochemical, rheological and biochemical properties, it is capable of forming a continuous matrix with the potential to become the reserve force for sustainable materials. To meet the specific requirements of its applications, different modification techniques, such as physical, chemical and enzymatic methods, have been used to increase or inhibit its inherent properties or to provide specific properties of starch (Li et al., 2017). Thus, starch is promising for the development of ecologically sustainable materials (Biduski et al., 2018; Xiao, 2013; Zhu et al., 2015).

Even more recent is its use in the food industry. In the last ten years, different types of starch-based hydrogels have been developed for food applications, in encapsulation promoting the controlled release of bioactive compounds, incorporation of beta carotene and evaluation of bioaccessibility in the gastrointestinal tract (Mun et al., 2015; Mun et al., 2015b; Mun et al., 2016; Park et al., 2018; Silva et al., 2021), encapsulation and control of release of antioxidant compounds (Doosti et al., 2019; Huamán-Leandro et al., 2020; Kulkarni et al., 2014; López-Córdoba et al., 2013), probiotic delivery system (Dafe et al., 2017) and control of yellow dye release in foods (Soares et al., 2021).

Hydrogels produced in different studies were developed with potential application of 3D food printing (Maniglia et al., 2019; Maniglia et al., 2020), production of "ink" for 3D food printing (Maniglia et al, 2020b). 3D printing aims to build a three-dimensional object from a computer-aided design model. Printing (3D) applied to food has a unique potential to create complex geometric structures, allowing for mass production while bringing economic and environmental benefits, allowing you to create personalized food from specific properties related to nutritional needs, caloric intake, specific shape, texture, color or taste, for example (Le-Bail et al., 2020).

Bioactive films based on starch hydrogels have also been extensively studied, with the aim of preserving food (Bekhit et al., 2018; Sharmin et al., 2020; Shchbazi et al. 2018; Soukalis et al., 2016).

The future of biopolymer-based materials is to show that natural sources, as they are renewable and used in a sustainable way, with less impact on the environment, can overcome the use of synthetic polymers derived from petroleum. The application of hydrogels obtained from polysaccharides in the food industry is constantly increasing, due to the high demand for natural and environmentally compatible materials (Huamán-Leandro, 2020; López-Córdoba et al., 2013).

Within this context, the aim of this work was to review studies that have investigated the applications of starch hydrogels in food.

2 METHODOLOGY

This is an integrative literature review, which aimed to answer the following question: "What are the applications of starch hydrogels in food?"

The first stage of this research consisted in the elaboration of the guiding question and through this, searches were performed in databases of scientific articles PUBMED (US National Library of Medicine), Science Direct and Web of Science. Data were collected in January and February 2021.

2.1 RESEARCH STRATEGY

Initially, exploratory searches were carried out in these databases with the terms: “starch”, “hydrogel or hydrogels”, to retrieve these subjects in the literature. The descriptors and keywords were combined with each other using the Boolean operators AND and OR, and thus the search strategy to be used in each platform was defined (Table 1).

Table 1. Search strategies defined for use in databases.

Database	Search strategy
PUBMED	"starch"[Title/Abstract] AND "hydrogel"[Title/Abstract]
Web of science	TÓPICO: (starch) AND TÍTULO: (hydrogels)
Science Direct	Title, abstract, keywords: starch AND hydrogels

Source: Autores (2021).

2.2 SELECTION CRITERIA

For inclusion of articles, the following criteria were adopted: studies available in full; published in the period from 2011 to 2021, and this period was stipulated for the analysis of techniques still applied today and that were not outdated, in Portuguese, English or Spanish, on starch hydrogels from conventional and unconventional sources, with technological applications in food. The exclusion criteria used in the selection were: studies of hydrogel production methods, without defined technological application and of hydrogels formed from sources other than starch; chemical and morphological characterization studies, thermal properties of starches and hydrogels; application in pharmaceuticals and biomedical.

2.3 DATA ANALYSIS

Regarding the selection of articles, two steps were performed. In the first stage, the titles and abstracts of the studies found on each platform were read and, with this, they were retrieved, as well as the exclusion of duplicates, with the help of Mendeley reference manager software and the preparation of a table containing title, abstract and keywords of the selected studies according to the inclusion and exclusion criteria described above, with the aid of Microsoft office Excel software. For the second stage, the articles selected in the first phase were read in their entirety and they were recorded, based on a careful selection, containing the information: title, year of publication, journal, authors, type of starch and modification, main results, and applications.

3 RESULTS AND DISCUSSION

A total of 176 articles were found in the PubMed database, 225 in the Web of Science and 227 in Science Direct, totaling 631 articles (Table 2).

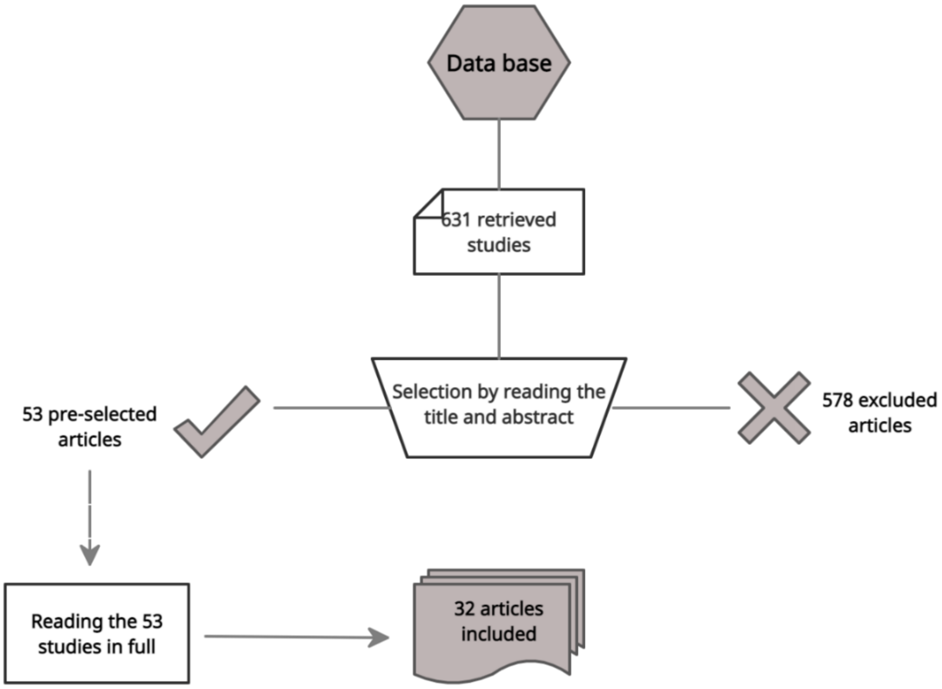
Table 2. Works retrieved in database research.

Database	**Number of articles**	**Total**
PubMed	176	631
Web of science	225	
Science Direct	227	

Source: Autores (2021).

Of these studies, 578 were excluded by analyzing the title and abstract, for not answering the guiding question of the review or for being duplicated in the databases, and 53 were read in full. In the end, 32 articles were selected to compose this review, on the applications of starch hydrogels in food, published between 2013 and 2021 and written in English. The selection process is shown in Figure 1.

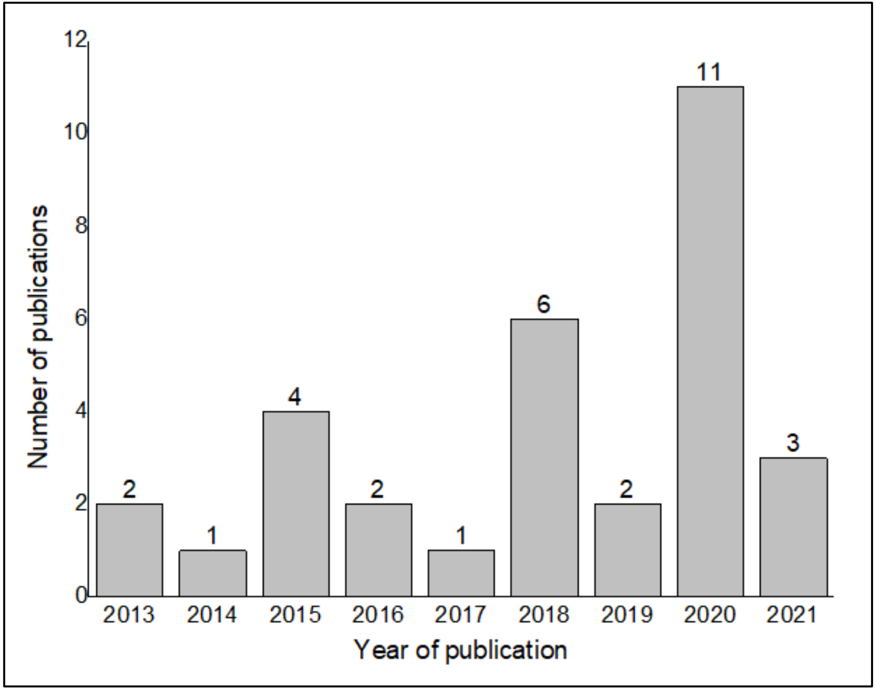
Figure 1. Flowchart of study selection criteria. Source: Authors (2021).



Source: Authors (2021).

The distribution of studies by year of publication is shown in Figure 2.

Figure 2. Number of articles per year of publication.



Source: Authors (2021).

Of the 32 articles selected, all are experimental studies. Of these, 13 are about hydrogels as encapsulating materials for the protection and control of release of bioactive substances (Doosti et al., 2019; Huamán-Leandro et al., 2020; Jain et al., 2020; Kang et al., 2021; Kulkarni et al., 2014; López-Córdoba et al., 2013; Meng et al., 2020; Mun and McClements, 2017; Mun et al., 2015b; Park et al., 2018; Silva et al., 2020; Silva et al., 2021; Wu and McClements, 2015), 5 about the development of films for food preservation (Bekhit et al., 2018; Sharmin et al., 2020; Shchbazi et al., 2018; Soukalis et al., 2016; Tosati et al., 2018) and 4 produced starch-based hydrogels for application in 3D food printing (Lima et al., 2020; Maniglia et al., 2019; Maniglia et al., 2020; Maniglia et al., 2020b).

The other studies evaluated proposed more diversified applications, namely: one for the application of the starch hydrogel as a dye release control system in food (Soares et al., 2021), one on the development of hydrogel as a delivery system for probiotics (Dafe et al., 2017), one on the production of a milk lipid (fatty acid) release system (Huang et al., 2020), one on the development of a low glycemic index gelling ingredient for application in food and beverages (Liu et al., 2020), one on the production of a functional hydrogel for application in food (Torres et al., 2020), one on the development of functional hydrogel with application in food and beverage to control the glycemic index (Liu et al., 2018), one on the development of oil-filled hydrogel particles as fat or starch substitutes in food (Chung et al., 2013), one on the formation of xerogel with potential use as an edible cereal snack (Ramanan et al., 2018), and one on the development of food matria in order to reduce Lipid digestion for application in functional foods (Tangsrianugul et al., 2015).

The summary of the results is presented in Table 3.

Table 3 Summary of selected studies

Starch	Hydrogel formation method	Application	Reference
Commercial soluble starch	Starch modified by the use of fumaric acid. Starch-based super paramagnetic hydrogel grafted with fumaric acid. Incorporation of quercetin (antioxidant flavonoid) into the hydrogel and its release was analyzed in vivo and in vitro.	The sustainability and bioavailability of quercetin increased in rats. According to the in vivo study, this hydrogel can increase the sustainability of Quercetin in plasma and delay its release, as well as increase liver maintenance.	(DOOSTI et al., 2019)
Potato	Potato starch in gelatinized and native forms was used in encapsulation systems. β-carotene was incorporated into hydrogels filled with an emulsion composed of alginate, gelatin, and starch (native and gelatinized). Emulsion-filled microgels were obtained by spraying.	The results point to possible applications of encapsulated carotene in acidic foods or those subject to temperature fluctuations after manufacture, increasing their shelf life and allowing controlled delivery.	(GUEDES SILVA et al., 2021)
Potato	Potato starch as a gelling agent. Autohydrolysis.	Preparation of bioactive hydrogel with mushroom extract. Functional hydrogels with attractive rheological characteristics offer new potential possibilities for the enhancement of *Lentinus edodes* extracts.	(HUAMÁN-LEANDRO et al., 2020)
Rice	Double modified rice starch (enzymatic debranching and OSA esterification methods)	Modified rice starch can be used as an innovative food grade material for the design of different delivery systems to improve the chemical stability of lycopene and its controlled release in the gastrointestinal tract.	(JAIN; WINUPRASITH; SUPHANTHARIKA, 2020)
Rice	Enzymatic modification, curcumin loaded emulsion to produce filled hydrogels	Possible applications include a biocompatible carrier for oral administration of sensitive functional food ingredients and in functional food coatings and packaging materials to extend the shelf life of food products.	(KANG et al., 2021)
Lagenaria siceraria seed	Lagenaria siceraria fruit extract Ca alginate hydrogel granules	The application of this technology would improve the stability of *Lagenaria siceraria* fruit extract in antioxidant pharmaceutical and food products.	(KULKARNI; SINHA; KUMAR, 2014)
Corn	Hydrogels formulated by ionic gelling. Calcium-starch alginate (CAS) hydrogels were obtained by adding different concentrations of commercial corn starch	Hydrogels reinforced with cornstarch granules have improved the classic calcium alginate system, leading to a promising strategy to protect and provide yerba mate antioxidants in food products.	(LÓPEZ CÓRDOBA; DELADINO; MARTINO, 2013)
Tapioca	Esterification of tapioca starch with maleic anhydride	Curcumin encapsulation (protection of bioactive substances)	(MENG et al., 2020)

Rice	β-carotene was incorporated into three types of delivery system: (I) "emulsions": protein-coated fat droplets dispersed in water; (II) "hydrogels": rice starch gels; and (III) "filled hydrogels": protein-coated fat droplets dispersed in rice starch gels.	The bioaccessibility of β-carotene was greater in filled hydrogels than in emulsions. Rice starch-based gel products fortified with lipophilic nutraceuticals.	(MUN; KIM; MCCLEMENTS, 2015)
Rice, mungu bean	Oil emulsion for the dispersion of beta carotene. Preparation of filled hydrogels.	Development of functional starch-based food products fortified with lipophilic bioactive components that can improve human health and well-being. Fortification of starch-based gelled products with lipophilic nutraceuticals.	(MUN et al., 2015)
Rice	Rice starch hydrogels, beta carotene encapsulated in lipid droplets that were loaded into rice starch hydrogels containing different levels of methylcellulose.	.Control the gastrointestinal fate of nutraceuticals to improve their effectiveness. Functional foods with better nutritional benefits.	(MUN et al., 2016)
Rice	Mixture of rice starch and xanthan gum	Lipid digestion and bioaccessibility of encapsulated beta carotene; food products with gel fortified with lipophilic nutraceuticals	(PARK; MUN; KIM, 2018)
Potato	Production of pH-dependent microgels by ionic gelling, coated with alginate and gelatin	It proved the ability of encapsulation systems to promote targeted delivery of bioactive compounds. The coating can be further functionalized by including bioactive or nutraceutical ingredients, expanding its applicability	(SILVA et al., 2020)
Modified commercial starch	Production of hydrogel microspheres from gelatin and starch modified with octenyl succinic anhydride (OSA starch).	Potential application to modify the texture of food products and to encapsulate flavor or bioactive compounds.	(WU; MCCLEMENTS, 2015)
Corn	Corn starch hydrogel microspheres and alginate-pectin	Production of bioactive films for food preservation.	(BEKHIT et al., 2018)
Corn	Cornstarch granules physically modified by means of a high-speed shear homogenizer. Hydrogel and film production.	Film production with good functional properties, improving water resistance and water barrier property, with potential application in the food packaging sector.	(SHAHBAZI; MAJZOOBI; FARAHNAKY, 2018)
Corn	Polyvinyl alcohol / corn starch / linseed polyol based hydrogel loaded with biosynthesized silver nanoparticles. Film Preparation.	Antimicrobial packaging.	(SHARMIN et al., 2020)
Rice, Corn	Edible hydrogels (rice or corn starch), gelatin, sodium caseinate	Incorporation into edible probiotic films	(SOUKOULIS et al., 2016)
Cassava	Cassava starch, curcumin, gelatin. Edible antimicrobial coating	The combination of hydrogel coatings loaded with curcumin and UV-A light has great potential as antimicrobial coatings to prevent cross-contamination of L. innocua in refrigerated sausages	(TOSATI et al., 2018)
Cassava	Dry heating treatment (DHT)	3D food printing	(LIMA, MANIGLIA et al., 2020)
Wheat	Dry Heat Modified Wheat Starch (DHT)	Formation of hydrogel to be used as "ink" for 3D food printing	(MANIGLIA et al., 2020)
Cassava	Ozone starch oxidation	3D food printing	(MANIGLIA et al., 2019)

Parsley manioc	Parsley cassava starch, modified by ozone technology, hydrogel formation	Ozonized cassava starch had harder gels than the native sample, which is promising for industrial use, since stronger gels are desired for products such as desserts, jelly candies and meat products (sausages). In addition, starch gels with greater firmness have aroused interest in the application of 3D food printing, with better printability	(LIMA et al., 2020)
Commercial soluble starch	Mixture of soluble starch and chitosan	Yellow Dye Release Control (INS 110). Retention or release of bioactive compounds or food additives	(SOARES et al., 2021)
Corn	Manufacture of new food grade hydrogel particles based on pectin and cornstarch for probiotic delivery. Pectin / starch hydrogels were prepared by the external gelling method at various pectin / starch ratios	Manufacturing functional products based on probiotics with the aim of improving the health of the human body, the results of this investigation offer potential substrates for the effective delivery of probiotic cultures as a functional food.	(DAFE et al., 2017)
Corn, wheat, rice	Three types of starch gels; release of free fatty acids by a multiple reaction model	This study offers a viable way to manipulate the lipid digestibility of milk by stabilizing with starch gels. The results provide useful means for the fabrication of new lipid matrices to encapsulate lipophilic nutraceuticals or to increase the digestibility of milk lipids in energy foods.	(HUANG et al., 2020)
Corn	Debranched cornstarch with different degrees of debranching were investigated to reveal the effects of molecular interactions on its digestibility and hydrogel properties.	Great potential in the preparation of stable hydrogels as low glycemic index gelling and clouding ingredients in the food industry: foods and beverages with defined functionalities or properties.	(LIU et al., 2020)
Potato	Production of whole potato starch hydrogels	Production of bioactive hydrogels for food application	(TORRES et al., 2020)
Corn	Enzymatically debranched waxy cornstarch (DBWS).	Potential applications of DBWS in food and beverage with stable quality due to its digestibility and hydrogel properties. Prolonged digestion and starch absorption are preferable not only for long-term glycemic control, but also in healthy individuals, as it favorably affects a number of physiological factors.	(LIU et al., 2018)
Corn	Modified cornstarch, sodium caseinate, canola oil. Oil-filled hydrogel particles formed in mixtures of starch and fat	Formulation of reduced calorie emulsion-based food products with enhanced physical and sensory attributes.	(CHUNG; DEGNER; MCCLEMENTS, 2013)
Wheat	Wheat Flour Hydrogel. Xerogel formation.	Xerogel obtained from wheat flour can be used as an edible cereal snack. The gel structure can be an alternative to the traditional dough structure for some functionalities in food systems. The xerogel developed can be impregnated with bioactive components in the development of functional foods and nutraceuticals	(RATISH RAMANAN; RIFNA; MAHENDRAN, 2018)
Corn	Normal corn starch (native), high amylose starch (resistant starch) compared to hydrogel formation	Designing functional foods that can slow down the rate of lipid digestion and therefore control serum triacylglycerol levels, developing functional foods for improved health. Development of functional foods to fight diabetes.	(TANGSRIANUGUL; SUPHANTHARIKA; MCCLEMENTS, 2015)

Source: Authors (2021).

3.1 APPLICATIONS OF HYDROGELS OF STARCH IN FOOD

The analysis of the results of the studies included in the elaboration of this integrative review allowed to demonstrate the high potential of hydrogels produced based on starch, in different food applications, which will be described below.

3.2 ENCAPSULATION AND RELEASE CONTROL OF BIOACTIVE SUBSTANCES IN HYDROGELS

The analysis of studies that developed hydrogels as a system to encapsulate and control the release of bioactive substances identified that this material was prepared using different sources of starch (conventional and unconventional).

Doosti et al. (2019) used commercial soluble starch to prepare a hydrogel and incorporated quercetin, an antioxidant flavonoid, and the release of this substance was analyzed in vivo and in vitro, concluding that bioavailability increased in rats and the release of antioxidant compounds was delayed by hydrogel system.

Silva et al. (2021) produced microgels composed of potato starch, alginate and gelatin, and β-carotene was incorporated, proposing possible applications of this encapsulated substance in acidic food, since the hydrogel allowed to control the delivery and increase the lifespan of beta carotene. Huamán-Leandro et al. (2020) carried out the extraction of components with antioxidant properties, from mushroom (*Lentinus edodes*) and incorporated it into potato starch hydrogel, then proposing the development of a functional, bioactive hydrogel, carrying a compound with high antioxidant capacity, for food applications.

In another study, rice starch was used doubly modified by enzymatic debranching and esterification, with the objective of producing a hydrogel as a controlled release system to improve the stability of lycopene in the gastrointestinal tract (Jain et al., 2020). Kang et al. (2021) also produced rice starch-based hydrogel and incorporated curcumin and proposed the following applications: biocompatible carrier for oral administration of functional food ingredients and as a food coating.

Calcium alginate hydrogel granules and *Lagenaria siceraria* fruit extract were produced, aiming to improve the stability of this extract in food products with antioxidant properties (Kulkarni et al., 2014). Another study prepared hydrogels also using calcium alginate in its composition, but with corn starch and incorporated yerba mate extract. This system has been proposed for promising applications with the aim of protecting and providing yerba mate antioxidants in foods (López-Cordoba et al., 2013).

Modified tapioca starch was used to produce a hydrogel as an encapsulating material to protect bioactive substances, providing a theoretical basis for its application in food, such as curcumin encapsulation (Meng et al., 2020).

In a study with the preparation of hydrogel based on rice starch, Mun et al. (2015) examined the influence of β-carotene incorporation and its bioaccessibility using a simulated gastrointestinal tract system. The application of the developed hydrogel was proposed for fortified products such as lipophilic nutraceuticals. Rice and mung bean starches, with oil emulsion, were the basis for the preparation of filled hydrogels. The proposed application was the use of this system in functional food products with lipophilic bioactive components (Mun et al., 2015).

Mun et al. (2016) carried out the encapsulation of β-carotene in hydrogels based on rice starch and methylcellulose, in order to control the gastrointestinal fate of this substance. The developed system proved to be useful for use in functional food. In another study, a rice starch and xanthan gum hydrogel was developed with the aim of encapsulating β-carotene and the application of this system in lipophilic nutraceuticals was proposed (Park et al., 2018).

Silva et al. (2020) performed an in vitro digestion assay of microgels composed of potato starch, alginate, and gelatin. The authors concluded that these microgels provided extra protection during digestion, which demonstrates the ability of encapsulation systems to promote targeted delivery of bioactive compounds.

The production of hydrogel microspheres from gelatin and commercial modified starch was carried out, demonstrating potential application in food products, with the objective of modifying the texture and encapsulating the flavor or bioactive compounds (Wu and McClements, 2015).

The presented studies prove that there has recently been considerable interest in the use of natural and quality materials for the encapsulation of different bioactive compounds. According to the data presented, it was possible to elucidate the benefits of developing adequate colloidal delivery systems, from natural sources, with the ability to release the encapsulated compounds in the proper place in the human body after ingestion, without causing undesirable effects to health.

3.3 FILM DEVELOPMENT

Starch hydrogels can also be used in food coating and bioactive packaging production. In this review, different studies produced these materials for this purpose.

Bekhit et al. (2018) produced films with corn starch hydrogel microspheres and alginate-pectin, as carriers of bacterial cells of *Lactococcus lactis*. These films containing encapsulated bioactive culture were able to completely inhibit listerial growth during the first five days of storage. In a study that also used corn starch but using a physical modification technique (high density shear homogenizer), it produced films with functional and resistant properties, with potential application in food packaging (Shchbazi et al., 2018).

Sharmin et al. (2020) carried out the preparation of a hydrogel film composed of polyvinyl alcohol, corn starch, and linseed polyol loaded with bio-systemized silver nanoparticles. The hydrogel film produced showed potential application in antimicrobial packaging.

Edible hydrogels based on rice or corn starch, proteins, and sodium caseinate were formed containing *Lactobacillus rhamnosus* and incorporated into films. Films produced based on rice starch showed greater stability than those produced based on corn starch, thus forming edible films with probiotic properties (Soukoulis et al., 2016).

Tosati et al. (2018) developed an edible antimicrobial coating for application to sausages. It was produced based on cassava starch, curcumin, and gelatin, with the formation of hydrogels with high antimicrobial activity when combined with UV-A light, suggesting that these hydrogels can be applied as edible coatings to inhibit contamination in embedded foods.

The results of the studies presented demonstrate that starch-based hydrogels constitute matrices that can act as effective carriers of antimicrobial agents, bioactive substances and thus be applied to the production of films, allowing their application in food packaging (control system substances that can increase the shelf life of food), and also directly as a food coating. In addition, the films are manufactured using an ecologically sustainable production strategy, benefiting human health and the environment.

3.4 3D FOOD PRINTS

Hydrogels produced based on different starch sources were developed with the purpose of providing materials that can be used as ingredients for 3D food printing technology.

In a study with cassava starch, Maniglia et al. (2020) developed a hydrogel through dry heat treatment (DTH), used to modify starch. The authors concluded that through this treatment, it was possible to obtain hydrogels with improved bonding properties, gel texture, and printability, increasing the potential of cassava starch application in 3D food printing.

The same research group used DTH again, but to modify wheat starch. In this study, a hydrogel was formulated with potential use as an "ink" for 3D food printing (Maniglia et al, 2020b). In another similar study, this group also developed hydrogels based on cassava starch, oxidized by ozonation. The authors demonstrated that ozone treatment is a relevant strategy for modifying cassava starch intended for 3D food printing (Maniglia et al., 2019).

Lima et al. (2020) developed a hydrogel based on parsley cassava starch, modified by ozone technology. Cassava starch modified by this technology had harder gels than the native sample, which is promising for industrial use, since stronger gels are desired for products, such as desserts, candies, jelly, and meat products (sausages). In addition, starch gels with greater firmness have aroused interest in the application of 3D printing on foods, with better printability, the study concluded.

The results of the presented studies demonstrate how starch-based hydrogels have potential applications for 3D food printing. 3D printing technology is gaining attention in the food industry as it can deliver new products. Starch hydrogel can improve the rheological properties of food matrices to achieve greater printability for 3D applications and improve their sensory attributes. This is due to its gel strength properties, consistent gel formation, structure, and printability properties.

3.5 OTHER FOOD APPLICATIONS

Several applications of starch hydrogels in foods were also presented in other studies included in this review.

Soares et al. (2021) developed a mixed hydrogel based on commercial soluble starch and chitosan, as a yellow dye release control system (INS 110), widely used to intensify the color in food.

A hydrogel based on corn starch and pectin was developed with the objective of manufacturing functional products, as an effective delivery system for probiotic cultures (Dafe et al., 2017). Huang et al. (2020) developed three types of corn, wheat and rice starch hydrogels, with the objective of manipulating the digestibility of milk lipids. The study provided, through these hydrogels, useful means for the manufacture of new lipid matrices to encapsulate lipophilic nutraceuticals or to increase the digestibility of milk lipids in energy food.

Liu et al. (2020) carried out the preparation of stable hydrogels, based on debranched corn starch, with great potential for application as gelling and clouding ingredients with a low glycemic index in the food industry. Another study developed bioactive hydrogels rich in phenolic compounds based on potato starch, using environmental friendly technologies and potentialized the full use of discarded potatoes. The hydrogel developed showed the ability to be applied in the food industry (Torres et al., 2020).

Through the technique of modification of waxy corn starch by enzymatic debranching, Liu et al. (2018) evaluated the molecular interactions and their effects on the digestibility and properties of the formed hydrogel, concluding that it has application capacity in food that aim to provide prolonged digestion and starch absorption, especially in relation to long-term glycemic control.

In a study carried out with modified corn starch, sodium caseinate and canola oil, Chung et al. (2013) developed mixed hydrogel particles, which increased lightness and viscosity in food products, demonstrating great potential for creating emulsion-based foods with reduced calories or products with enhanced sensory characteristics.

Ramanan et al. (2018) developed a xerogel using wheat flour, and proposed its use as a “snack” of edible cereals, which could be incorporated with bioactive compounds for the development of suitable foods and nutraceuticals. Still with the same objective in food development, another study produced hydrogels based on cornstarch, as an encapsulation system for corn oil droplets, using a simulated gastrointestinal tract model. The system produced was able to decrease the lipid digestion rate (Tangsrianugul et al., 2015).

4 FINAL CONSIDERATIONS

The analysis of different studies has allowed to identify several possible applications for starch hydrogels in the food area. Most of the studies in this review developed starch hydrogels and proposed specific applications for food. However, some did not reach the point of experimental testing of the proposed application, suggesting that the applications of the developed matrices for future research, or even for the industry. This demonstrates that the use of hydrogels in the food area is on the rise, and further studies are indicated that carry out experimental research on these applications.

5 CONCLUSION

Based on the articles analyzed in this review on the application of starch hydrogels in food, it was possible to conclude that there is a growing and current interest in the development of this product with the objective of improving sensory characteristics of food, proposing sustainable delivery systems for bioactive substances, development of films for food preservation and new technologies for 3D food printing.

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