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IMMOBILIZATION OF BIOACTIVE COMPOUNDS IN XANTHAN-BASED HYDROGELS: MECHANISMS, PRACTICAL APPROACHES AND CONCEPTS FOR THE DEVELOPMENT OF INNOVATIVE MATERIALS

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Abstract

The paper summarizes current approaches to the development of xanthan (XG)-oriented immobilization systems that ensure effective retention of bioactive compounds and heavy metal ions as bioactive toxicants. For the first time, the features of the formation of "xanthan–(modifier)–immobilization object" systems are considered. It is established that non-covalent interactions play a key role in the stabilization of immobilized objects. It is shown that the carboxyl, pyruvate, acetyl, and hydroxyl groups of xanthan provide effective interaction with cations of both biogenic and toxic metals, as well as with protonated functional groups of bioactive (including pharmaceuticals) and toxic (including dyes) compounds, ensuring their reliable retention within a three-dimensional hydrogel matrix. Such a structure creates prerequisites for controlled release and targeted delivery of bioactive substances, as well as for the binding and subsequent biodegradation of toxicants. The paper presents a classification of immobilization types based on retention mechanisms. The key role of ion-exchange immobilization in forming a porous polymer network capable of physically retaining additionally introduced molecules bioactive molecules is highlighted. The prospects for the application of such systems in pharmaceutical technologies and environmental processes are analyzed. Special attention is paid to composite materials with magnetic nanoparticles, which enable controlled transport and recovery of immobilized components. Previously, we established the absence of a unified protocol for quantum chemical modeling (QCM) as a tool for predicting interactions in "xanthan–(modifier)–immobilization object" systems. Therefore, this study substantiates the feasibility of applying QCM methods, in particular for determining stable conformations and identifying active binding sites. It is shown that the lack of such studies limits the systematization of results, necessitating the development of standardized approaches based on simplified structural fragments. The proposed approaches provide a theoretical framework for the targeted design of innovative functional materials.

Keywords: xanthan gum; hydrogels; immobilization; ionic interactions; coordination interactions; bioactive compounds; innovative materials.

ІММОБІЛІЗАЦІЯ БІОАКТИВНИХ СПОЛУК У ГІДРОГЕЛЯХ НА ОСНОВІ КСАНТАНУ: МЕХАНІЗМИ, ПРАКТИЧНІ ПІДХОДИ ТА КОНЦЕПЦІЇ РОЗРОБЛЕННЯ ІННОВАЦІЙНИХ МАТЕРІАЛІВ

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Анотація

У статті узагальнено інформацію щодо створення сучасних ксантан-орієнтованих систем, створених для іммобілізації біоактивних речовин і біоактивних токсикантів. Уперше розглянуті особливості формування систем типу «ксантан–(модифікатор)–об'єкт іммобілізації». Встановлено, що ключову роль у стабілізації іммобілізованих об'єктів відіграють нековалентні взаємодії між карбоксильними, піруватними групами ксантану з катіонами як біогенних, так і токсичних металів, а також із протонованими функціональними групами біоактивних (зокрема лікарських засобів) і токсичних (зокрема барвників) сполук. Така структура створює передумови для контрольованого вивільнення та таргетної доставки біологічно активних речовин або для зв'язування та подальшої біодеградації токсикантів. У статті наведено класифікацію видів іммобілізації, де враховано механізми утримання об'єктів. Проаналізовано існуючі перспективи застосування таких систем у фармацевтичних та екотехнологіях. В статті обґрунтовано доцільність використання засобів квантово-хімічного моделювання зокрема для визначення стабільних конформацій і ідентифікації активних центрів зв'язування. Встановлено, що відсутність квантово-хімічних досліджень обмежує можливості їх систематизації, що визначає необхідність розроблення стандартизованих підходів із використанням спрощених структурних фрагментів. Наведені пропозиції формують теоретичну основу для цілеспрямованого проєктування інноваційних функціональних матеріалів.

Ключові слова: ксантанова камедь; гідрогелі; іммобілізація; іонні взаємодії; координаційні взаємодії; біоактивні сполуки; інноваційні матеріали.

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Introduction

The rapid development of industry is accompanied by an increase in anthropogenic pressure on the environment, manifested in the accumulation of pollutants in soils and aquatic ecosystems. The main sources of such contamination are industrial waste and insufficiently treated wastewater containing heavy metals and other toxic compounds. These substances are characterized by high chemical stability, the ability to bioaccumulate, and significant toxicity, which leads to the formation of long-term environmental risks and complicates their elimination from natural environments. Even small amounts of these substances in the human body can cause severe dysfunctions of the nervous, cardiovascular, and endocrine systems, as well as the kidneys, liver, and gastrointestinal tract [1].

In this regard, the prevention of toxicant release into the environment and their effective removal from natural systems is a priority, as it represents a more rational approach compared to the subsequent application of complex therapeutic systems. Heavy metals pose a particular threat due to their ability to induce a wide range of pathological conditions, including inflammatory processes, tissue damage, impairment of mucosal functions, as well as dysregulation of microbiota and immune responses. At the same time, the development of pathological conditions is not solely determined by the presence of pollutants in soil and aquatic environments. Chronic stress and improper nutrition also play a significant role, contributing to the development of a wide spectrum of chronic diseases and metabolic disorders. This necessitates the development of advanced systems for targeted drug delivery to specific organs. In this context, the design of effective systems with controlled release and prolonged action, particularly those based on immobilized bioactive components, is of considerable relevance.

Immobilization is a targeted technological process involving the fixation of biological or non-biological objects (enzymes, cells, bioactive compounds, ions, molecules) within a matrix or on the surface of a carrier, with restriction of their spatial mobility while preserving or controllably modifying their functional activity. This approach ensures enhanced stability of the immobilized objects, protection against destabilizing environmental factors, and the possibility of controlling mass transfer, interactions, and release processes [2].

Xanthan gum (XG) has been used as a biopolymer in various industrial technologies since the 1960s, attracting considerable attention due to its biocompatibility, non-toxicity, and absence of irritant effects on skin and mucous membranes. Recent studies demonstrate that the structural features and polyelectrolyte nature of XG determine its ability to form stable hydrogel systems and to participate in a wide range of intermolecular interactions.

In our previous study, current concepts of gelation mechanisms and modification pathways of XG were systematized, and directions of its industrial and pharmaceutical applications were outlined. Further quantum chemical modeling (QCM) made it possible to identify energetically stable conformations of the polysaccharide and to determine functional groups capable of participating in noncovalent and coordination interactions [3].

The obtained results made it possible to explain the mechanisms, approaches, and objects of immobilization of bioactive compounds in xanthan gum (XG)-based hydrogels. At the same time, it should be noted that, to date, review materials on this topic remain insufficient, which determines the relevance of the present study.

In this review, materials from the last decade indexed in the ScienceDirect database have been analyzed. A limitation of available data regarding the types and methods of immobilization of active substances within the xanthan structure has been identified; the existing results are predominantly speculative or presented as practical implementations lacking sufficient theoretical justification. Moreover, there is a lack of systematic analysis of the mechanisms of immobilization of active components in xanthan-based carriers, which could enhance the level of research in soil and wastewater remediation, the development of effective drug delivery systems, and technologies for new functional materials.

This review summarizes data on ecotechnologies in which the immobilized objects include heavy metals, radionuclides, agrochemicals, dyes, and biological agents.

Particular attention is paid to pharmaceutical systems that require protection from light, oxygen, and the acidic gastric environment, as well as the provision of controlled release.

Approaches to the modification of xanthan gum and the formation of composite materials based on it are also considered. Such systems are capable of ensuring effective immobilization, stabilization, and transport of bioactive objects, as well as

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controlled fixation of toxicants with their subsequent removal or neutralization.

It is emphasized that xanthan gum combines structural and functional characteristics that define it as a promising biopolymeric platform for the development of materials with immobilization (encapsulation) functionality for various objects, thereby enabling their safe application in detoxification technologies and targeted delivery systems.

Theoretical Background. Xanthan gum belongs to the class of uronate polysaccharides due to the presence of glucuronic acid in its structure. Its complex supramolecular organization comprises a β-D-(1→4)-glucan backbone bearing trisaccharide side chains, which include glucuronic acid and mannose residues located on both sides of the acidic moiety. The structural specificity is determined by the presence of acetyl groups (predominantly at the 0–6 position of internal mannose residues) and pyruvate substituents on terminal mannose units, which confer a polyanionic character to the macromolecule.

The functional groups of XG (carboxyl, acetyl, and pyruvate) determine its participation in ionic and coordination interactions, including binding with cations and the formation of hydrogen bonds with macromolecules of various origins. This enables the formation of three-dimensional polymer matrices with varying consistency and degrees of macromolecular association, governed by the formation of double-helical conformations stabilized by intermolecular hydrogen bonding. It has been established that the aggregation state of the resulting structures is influenced by the ionic strength of the medium and the nature of the interacting components.

In particular, an increase in the concentration of di- and trivalent cations promotes the densification of the gel network due to ionic binding, accompanied by a decrease in porosity and an increase in the elastic properties of the system. At the same time, hydrogen bonding and interchain interactions ensure the stabilization of double-helical conformations and the formation of stable hydrogels.

Xanthan gum readily forms hydrogels in both cold and hot water, exhibits pseudoplastic behavior, and maintains stability over a wide pH range (2–12), which allows it to form stable hydrogel matrices suitable for the immobilization (encapsulation) of bioactive compounds [3]. In particular, the spatially organized gel structure enables the retention of molecules or particles of different nature, while the presence of functional groups and the variability of supramolecular organization facilitate the implementation of various interaction mechanisms, including physical entrapment, hydrogen bonding, ionic interactions, etc. This substantiates the potential of XG as a base material for the development of innovative immobilization systems, which aligns with the objective of this study.

Analytical Review

Xanthan is a natural polymer synthesized from renewable resources; therefore, its distinctive characteristics–such as biocompatibility, biodegradability, bioadhesiveness, and non-toxicity–combined with wide availability and low cost, explain its increasing application in the development of products not only for food, biomedical, and cosmetic uses, but also for soil remediation from heavy metals and agrochemicals, as well as for wastewater treatment from toxic contaminants.

Xanthan hydrogels represent three-dimensional networks with gel-like properties formed due to the establishment of an ordered and rigid double-helical structure at low temperatures or high ionic strength of the medium. The biopolymer chains are interconnected by weak intermolecular interactions, which do not ensure the formation of sufficiently rigid gels. Therefore, to improve structural characteristics and enhance the efficiency of immobilization processes, XG-based systems require the incorporation of additional components, the analysis of which and their influence on the structure of immobilization matrices will be discussed further [4].

1. Immobilization of substances in the presence of metals: mechanisms of formation and functional properties of matrices. One of the promising approaches to modifying xanthan-based carriers for the immobilization of bioactive compounds is the use of divalent ions, particularly Ca^{2+}, which are capable of significantly altering the structural and rheological characteristics of the polymer matrix. In study [5], the effectiveness of XG as a bioadhesive base for the development of buccal delivery systems of buspirone hydrochloride with controlled release was demonstrated.

It was shown that immobilization of the active compound enhances its bioavailability by avoiding the first-pass metabolism in the liver, which is a typical limitation for oral administration of this substance. The introduction of calcium sulfate as a source of Ca^{2+} ions plays a crucial role in regulating the system properties. Calcium ions interact with the carboxyl groups of glucuronic

acid residues, leading to conformational changes in the polymer chains. Contrary to classical concepts of ion-induced crosslinking as a factor that slows down release, this system exhibited a decrease in viscosity, degree of hydration, and swelling of the polymer, which, in turn, contributed to accelerated release of the drug substance.

The obtained results indicate the complex nature of interactions between XG and Me^{2+} ions, which is not limited to the formation of rigid crosslinked structures but also involves restructuring of the hydration shell and spatial organization of the polymer network. This opens new possibilities for regulating the release kinetics of bioactive compounds through targeted ionic modification [5].

The authors of [6] also described a xanthan-based matrix crosslinked with calcium ions; however, in that case, it was used for the immobilization of other objects–living cells, which will be discussed further.

An interesting study investigated the effect of the solubility of metal salts, particularly calcium salts, on the rheological and adsorption properties of xanthan hydrogels, especially in the context of changes in the conformational state of polymer chains and their interactions with solid surfaces. It was shown that, regardless of the type of salt, polymer solutions remain pseudoplastic; however, the nature of the ions significantly affects flow parameters [7]. The authors note that soluble calcium salts ($CaCl_2$, $Ca(NO_3)_2$) at low and medium concentrations reduce system structuring, i.e., they increase disorder by promoting macromolecular expansion, whereas at higher concentrations, partial reverse effects are observed. In contrast, insoluble salts ($CaSO_4$, $CaCO_3$, $Ca_3(PO_4)_2$) increase the effective viscosity of the system due to the formation of additional structural elements (insoluble particles) in the dispersed medium.

The interaction mechanisms between the medium (xanthan hydrogel) and the modifying objects (metal ions and their salt molecules) involve several monomeric units of XG, leading to intra- or interchain ionic crosslinking and determining the degree of polymer folding and rigidity. Adsorption studies on Si/SiO_2 surfaces revealed the formation of a bilayer structure: a dense, acid-resistant sublayer composed of highly entangled chains and a looser ზედ layer whose morphology depends on the type of calcium salt. Thus, calcium ions act as regulators of both rheological behavior and surface organization of XG, modulating its conformation, degree of association, and adsorption capacity without the formation of covalent bonds.

In study [8], XG was used as a functional biopolymer additive for the immobilization of heavy metal ions (Cd^{2+}, Cu^{2+}, Pb^{2+}, Zn^{2+}) directly in soil. The biopolymer retains a negative charge over a wide pH range, which facilitates effective binding of metal cations through mechanisms of electrostatic adsorption, ion exchange, and complexation in soils. The efficiency of heavy metal binding increases with XG concentration. At the same time, such approaches require further investigation of binding stability under variable environmental conditions, particularly fluctuations in pH and soil biological activity, which determine their prospects for practical application in remediation technologies.

In addition, it was shown that polymer modification, particularly via graft copolymerization, crosslinking (e.g., using trimethylolpropane triglycidyl ether), and the introduction of crosslinking agents (acrylic acid, acrylamide, nitrogen-containing vinyl monomers), significantly enhances adsorption capacity and selectivity toward Zn(II), Pb(II), Cu(II), Ni(II), Co(II), Mn(II), Cr(II), and Hg(II). The authors of [8] demonstrated that immobilization efficiency is determined by the presence of carboxyl and hydroxyl groups, as well as by the structural characteristics of the hydrogel network, including the degree of swelling and porosity.

The prospects for the use of XG in hydrogels, nanocomposites, and magnetic biosorbents for heavy metal immobilization via sorption, ion exchange, and complexation have also been described. In particular, it has been shown that the incorporation of inorganic fillers or magnetic nanoparticles enhances the removal efficiency of Pb(II), Cu(II), and Ni(II), while enabling convenient separation of the sorbent after treatment [9]. Moreover, the authors highlight the potential of XG as a matrix for the immobilization of microorganisms in bioremediation systems, thereby expanding its applicability in integrated environmental purification technologies.

In study [10], a novel bionanocomposite based on XG, N-acetylcysteine, and modified mica was developed for the removal of toxic Pb(II), Cu(II), and Ni(II) ions from aqueous environments. In the synthesized material, mica serves as a mineral nanofiller, enhancing mechanical and thermal stability and providing a large number of binding sites. N-acetylcysteine acts as an active ligand, creating additional coordination-active centers. In

addition to the functional groups of xanthan involved in binding, the thiol groups of N-acetyl-cysteine can also participate in complexation and chelation of heavy metal cations [10].

The xanthan–chitosan (XG/CS) hydrogel described in [11] is a promising biopolymeric adsorbent in which the combination of polyanionic (xanthan gum, $-COO^-$) and polycationic (chitosan, $-NH_3^+$) components ensures the formation of a dense three-dimensional network with a high concentration of active sites. The study experimentally confirmed effective binding of heavy metal ions Cd^{2+}, Ni^{2+}, and Cu^{2+} in the presence of water-soluble salts $Cd(NO_3)_2$, $Ni(NO_3)_2$, and $CuSO_4$. The binding mechanism is realized through a combination of electrostatic interactions between polymer functional groups and hydrated metal cations, chelation involving carboxyl, amino, and hydroxyl groups, as well as ion exchange, resulting in the formation of stable coordination complexes within the hydrogel structure.

This system demonstrates significant potential for application in industrial wastewater treatment technologies, particularly in the metallurgical, electroplating, and mining industries [11].

Trivalent metals have also attracted considerable research attention: a substantial portion of recent studies on immobilization processes in XG-based systems is devoted to the immobilization of Fe^{3+} ions and Fe_3O_4 particles within xanthan hydrogel matrices. A number of studies have shown that immobilization proceeds via an ion-exchange mechanism, similar to that observed for Me^{2+} cations, involving carboxyl groups and pyruvate moieties of XG.

The introduction of Fe(III) cations into the hydrogel matrix leads to structural reinforcement, the formation of a relatively homogeneous layered morphology, and an increased swelling capacity [4]. At the same time, the xanthan matrix stabilizes biogenic FeS nanoparticles, maintaining their dispersed state and preventing aggregation [12], and also serves as a basis for the formation of nanofibers derived from xanthan modified with thiosemicarbazide [13]. In the former cases, the developed systems demonstrate effectiveness in wastewater treatment processes for Pb(II) and U(VI), respectively, while the latter composition shows promise for applications in biomedical materials and sensor systems.

Systems incorporating immobilized magnetic iron oxide nanoparticles (Fe_3O_4) have proven particularly promising. These nanoparticles act as an active nanophase capable of electrostatic interaction with carboxyl groups of XG, as well as hydrogen bonding with hydrophilic drug molecules [14]. In such systems, the incorporation of magnetic nanoparticles imparts magneto-responsive properties to the hydrogel, enabling stimulus-controlled drug release. Under an alternating magnetic field, the nanoparticles generate localized heat (magnetic hyperthermia effect), leading to partial disruption of the polymer network, a decrease in viscosity, and enhanced diffusion of the encapsulated substance. As a result, the drug release rate can significantly increase compared to passive conditions.

Thus, systems of the "XG–Fe_3O_4–bioactive compound" type represent integrated functional platforms combining immobilization mechanisms (electrostatic interactions, hydrogen bonding, physical entrapment) with externally induced controlled release. In these systems, ion-exchange immobilization and physical retention (entrapment) are realized. It should be emphasized that such approaches enable the transition from conventional hydrogel carriers to advanced "smart" materials with tunable properties, opening broad prospects for their application in targeted therapy, wound healing, and regenerative medicine [14].

In study [15], amoxicillin molecules were used as the immobilized object. The xanthan hydrogel matrix provides conditions for controlled diffusion-based drug release. The incorporation of Fe_3O_4 nanoparticles, which function both as a physical crosslinking agent and a magneto-responsive filler, enables controlled modulation of mass transfer kinetics of the bioactive substance under the influence of an external magnetic field.

In study [16], an Fe_3O_4–XG nanocomposite was used as a functional additive for the modification of polyvinylidene fluoride (PVDF) membranes via the phase inversion method. It was demonstrated that the incorporation of XG enhances membrane hydrophilicity, permeability, antifouling, and antibacterial properties, as well as improves the efficiency of dye and protein separation.

In another study, a magnetic hybrid composite Fe_3O_4@SiO_2–XG was developed for the selective adsorption and subsequent recovery of Pb^{2+} from aqueous solutions and industrial lead-containing wastewater. The composite was synthesized via a sol–gel process using tetraethyl orthosilicate (TEOS): during synthesis, a silica network was formed on the surface of Fe_3O_4 particles, while XG molecules were simultaneously immobilized on the silica surface under acidic conditions [17].

A number of studies report the immobilization of other metals, including gold nanoparticles [18] incorporated into an XG/CS system modified with glutaraldehyde, aimed at forming a long-acting catalyst for nitroarene reduction reactions in aqueous media (for the treatment of wastewater from chemical and pharmaceutical industries), as well as titanium dioxide (TiO_2) [19] for the development of an efficient and technologically convenient photocatalyst for the removal of the toxic dye methyl orange from water.

In study [20], the use of Zn(II) cations within a guar–xanthan matrix is described for the fabrication of a robust 3D-printed scaffold for localized delivery of thymol in complexes with hydroxypropyl-β-cyclodextrin to wound sites.

As follows from the presented results, metal ions contribute to the formation of a three-dimensional network that exhibits retention capacity for immobilized objects and enhances the structural integrity of hydrogels. The following sections present practical results and describe the mechanisms of other types of immobilization processes involving XG.

2. Immobilization of drugs: targeted delivery and controlled release. In modern studies on the immobilization of pharmaceutical compounds aimed at prolonging release, enhancing gastroretention, enabling colon-targeted delivery, and protecting sensitive molecules from premature degradation in the gastrointestinal tract, XG is considered a universal polymer matrix for the formation of various types of carriers, including matrix tablets, polyelectrolyte complexes, microspheres, nanoparticles, and hydrogels.

In study [21], the mechanisms of formation of XG-based carriers reinforced with Al^{3+} for the delivery of metformin hydrochloride are described. Notably, an increase in XG concentration leads to the formation of a denser and more stable hydrogel matrix, resulting in higher encapsulation efficiency (up to 93.11%), reduced premature release of the active substance, and the formation of a prolonged release profile, particularly at pH 6.8, whereas limited release is observed under acidic conditions (pH 1.2). It was established that the retention mechanism of metformin is predominantly governed by physical entrapment within the polymer matrix without the formation of covalent bonds, as confirmed by FTIR analysis.

A number of other studies report the immobilization of pharmaceutical compounds belonging to different classes of organic substances, i.e., possessing diverse structures and, most importantly, different functional groups involved in binding within matrix XG-based hydrogels. Thus, the study [22] resulted in the development of an effective buccal delivery system for tannic acid based on XG for the treatment of sialorrhea. This approach modifies conventional administration strategies (particularly oral delivery), minimizing the first-pass effect and enzymatic degradation of the active substance. XG was modified via covalent attachment of the amino acid L-cysteine to the carboxyl groups of the polysaccharide, forming amide bonds in the presence of a carbodiimide activator (EDAC) and a stabilizer (NHS).

In another study, a hydrophilic XG polymer matrix was used for the incorporation of pentoxifylline [23]. The properties of a magnetic nanocomposite based on nickel nanowires immobilized within an XG/CS matrix were described in [24]. The resulting biocompatible material demonstrates potential for controlled drug delivery systems. Particular attention should be paid to the synthesis features of such composites, which involve mixing aqueous solutions of XG and CS followed by pH adjustment, leading to the formation of a polyelectrolyte complex. In this system, XG performs both structural and coordination–sorption functions due to ion-exchange processes, while chitosan enhances mechanical strength and matrix stability and participates in the ion-exchange immobilization of nickel nanowires.

Improved immobilization of the toxic carcinogenic dye crystal violet in an XG-based system has also been reported, where the biopolymer was preliminary modified with synthetic compounds such as acrylamide and triglycidyl ether [25].

In study [26], the effectiveness of ion-sensitive xanthan hydrogels modified with succinic anhydride for the immobilization of the antibacterial agent gentamicin was demonstrated. In such systems, gentamicin is released in a prolonged manner while retaining its biological activity. Immobilization of gentamicin occurs without covalent bond formation and is conditioned by its retention within the three-dimensional polymer network. The fixation of the antibiotic is achieved through spatial confinement within the hydrogel pores and a combination of noncovalent interactions, primarily electrostatic interactions between the carboxyl groups of the polymer and the amino groups of gentamicin, as well as hydrogen bonding. This mechanism

ensures stable retention of the bioactive compound with the possibility of controlled release under the influence of ionic strength.

A similar mechanism is observed in xanthan-based hydrogels modified with acrylic acid, where ciprofloxacin acts as the immobilized object [27]. In such systems, immobilization is governed by noncovalent interactions—primarily electrostatic interactions and hydrogen bonding—in combination with the physical entrapment of molecules within the porous hydrogel structure, resulting in a comparable profile of prolonged and controlled release.

A similar principle of matrix formation is observed in systems with polyacrylamide; however, in the case of sodium diclofenac immobilization, ion-exchange interactions are additionally involved. The combination of xanthan with konjac glucomannan enables the formation of systems with pronounced intermolecular hydrogen bonding, which suppresses drug diffusion while simultaneously allowing controlled prolonged release of theophylline. In the case of composite xanthan hydrogels with hydroxypropyl methylcellulose, systems with controlled release of metoprolol succinate are obtained.

Numerous developments also involve chitosan, where negatively charged carboxyl groups of xanthan interact with positively charged amino groups of chitosan, ensuring controlled diffusion of drugs (e.g., neomycin) and antioxidant compounds (e.g., curcumin) with the possibility of their targeted delivery. A model of gastroretentive floating tablets based on xanthan with various modifiers has been developed to enhance oral bioavailability [28].

For compression-coated systems intended for colon-targeted delivery, xanthan was used for the immobilization of 5-fluorouracil in combination with Boswellia gum, where the release of the active substance is triggered by the microbiota of the large intestine, confirming the biodegradability of xanthan. In nanoscale systems, particularly in pH-sensitive nanoparticles based on modified xanthan (PAAm-g-XG), curcumin was immobilized, with release control governed by ionization of carboxyl groups and pore formation within the particle structure under pH variation. For mesalamine, microspheres based on xanthan–guar mixtures combined with probiotics were proposed, where the xanthan-based carrier simultaneously functions as a prebiotic medium. Similar approaches have also been applied for the delivery of indomethacin [28].

A separate research direction involves the immobilization of proteins and peptides, including BSA, selenium-containing peptides, vancomycin, and daptomycin, where xanthan-based hydrogels, microparticles, and nanoparticles serve not only as carriers but also contribute to the preservation of structural integrity and enhanced stability of biomolecules. The cited studies describe mechanisms of physical entrapment, ionic binding, hydrogen association, pH-responsive release, and carrier biodegradation under the action of microbiota, which positions xanthan-based systems as a promising platform for the development of innovative materials for controlled and targeted delivery [28].

Thus, the described systems are characterized by regulated mass transfer kinetics. Similar interaction principles are also realized in the immobilization of biomacromolecules, particularly enzymes; however, in this case, special importance is attributed to maintaining their conformational stability and catalytic activity.

3. Immobilization of enzymes: structural organization and functional properties. A number of studies have established that enzyme immobilization on solid carriers is achieved through physical (adsorption, affinity and ionic binding, entrapment, encapsulation) and chemical (covalent binding, crosslinking) approaches, with the choice of mechanism determined by the nature of the matrix and the required stability of the system [29; 30]. Chemical methods, particularly covalent binding, provide higher enzyme stability due to the formation of strong bonds, although they may affect the conformation of the active site. In contrast, physical interactions (van der Waals forces, hydrogen bonding, electrostatic interactions) are more mild but less stable.

The efficiency of immobilized systems is determined by achieving functional compatibility between the enzyme and the matrix, which includes preservation of native conformation, accessibility of active sites, and optimal mass transfer conditions. Disruption of this compatibility may result from matrix rigidity, diffusion limitations, exposure to organic solvents, enzyme desorption, or mismatch of functional groups of the carrier. To enhance stability, modifying agents are employed (see below), which provide additional crosslinking and structural stabilization of the polymer matrix [29].

Polysaccharide matrices based on XG are of particular interest, as they combine a polyanionic nature, hydrophilicity, and the ability to form

structured hydrogels. The presence of carboxyl and pyruvate groups enables ionic, hydrogen, and coordination interactions with protein molecules, as well as structural modification through the introduction of cations or crosslinking agents. As a result, stable and permeable matrices with controlled rheological properties are formed, promoting the preservation of enzyme activity and the development of functionally tunable biocatalytic systems [30].

A universal and highly efficient method for the immobilization of biochemically active substances (enzymes, microorganisms, and cells) using xanthan gum (XG) as a safe natural carrier was proposed in patent [31]. The method is based on ion-exchange processes involving metal ions (primarily Al^{3+} and Fe^{3+}), which ensure rapid formation of a porous gel followed by the "entrapment" and retention of the bio-object within its structure. This approach enables the formation of immobilized systems with different morphologies (beads, fibers, particles) depending on the method of solution introduction, as well as the regulation of matrix density and mechanical properties. The main objective of this development is to overcome the limitations of traditional immobilization methods (toxicity of monomers, low stability, and loss of activity), which is achieved due to the biocompatibility and thermo- and pH-stability of XG. The proposed system ensures the preservation of functional activity of the immobilized objects and allows for their repeated use.

The objects of immobilization included enzymes (invertase, protease, lipase), microorganisms (*Xanthomonas campestris*, *Saccharomyces cerevisiae*, *Rhizopus*), and cellular systems. A key feature is the selected immobilization method—mixing the bio-object with a solution of XG or its derivatives followed by gel formation in the presence of metal ions. For microorganisms, the possibility of prolonged cultivation without loss of productivity was demonstrated, which simplifies technological processes and eliminates the need for repeated inoculation.

It was experimentally confirmed that hybrid $CaCO_3$/XG microspheres can be obtained via biomimetic mineralization through the precipitation of calcium carbonate from $CaCl_2$ and Na_2CO_3 solutions within a xanthan-containing hydrogel. Although XG does not directly participate in the precipitation reaction, it significantly influences the crystallization process, particularly the size, morphology, and spatial organization of $CaCO_3$ particles. The obtained microspheres were used as carriers for lysozyme immobilization via electrostatic interactions between charged groups of the protein and the matrix surface. It was shown that the adsorption efficiency depends on the pH of the medium and increases under alkaline conditions [32].

In study [33], the ability of a chitosan/xanthan (CS/XG)-based system to form bilayer nanocapsules for stepwise immobilization of lipase was demonstrated. At the first stage, the carboxyl groups of lipase interact with protonated amino groups of chitosan. At the second stage, XG forms an outer layer through interactions of its carboxyl groups with cationic centers of chitosan, resulting in the formation of a polyelectrolyte complex.

In other studies, using the same principle and carrier, trypsin [34] and endo-1,4-β-xylanase [35] were immobilized. The authors also reported increased enzyme activity, improved thermal protection, and enhanced performance in organic media [32]. Morphological analysis of the carrier revealed that the hydrogel matrix exhibits a fibrillar structure with spatial variability, within which localized compact quasi-spherical domains are formed. These domains function as microtraps where spatial retention of the enzyme (physical immobilization) occurs: they limit diffusion, prevent leaching, and create a stabilizing microenvironment that affects the kinetic parameters of the system [35].

In study [36], the formation of a hybrid nanobiocatalyst was demonstrated for the first time via the growth of β-galactosidase–manganese nanoflowers on electrospun polycaprolactone (PCL)/XG nanofibers, aimed at enhancing lactose hydrolysis efficiency and overcoming typical limitations of soluble enzymes, such as low stability, difficulty in separation, and lack of reusability.

The discussed approaches are also relevant for the immobilization of microorganisms. However, in this case, the system becomes more complex due to the need to ensure not only structural stability but also the viability and metabolic activity of the cells.

4. *Immobilization of living microorganisms: factors of viability preservation and transport.* The materials of study [6] emphasize the use of biocompatible crosslinking methods (in particular, using Ca^{2+} ions) and consider the immobilization of living cells for wastewater treatment. Xanthan enhances microbial survival, reduces cell leakage, and improves matrix stability

under harsh conditions, particularly in wastewater environments.

These agents are relatively biocompatible, allowing the preservation of the viability of immobilized cells, whereas the use of more aggressive chemical crosslinkers, in our view, is limited due to their toxicity. As noted in the study, the combination of citric acid and glycerol within the XG hydrogel exhibits an inert effect on living microorganisms. The role of citric acid consists in covalent crosslinking via esterification of hydroxyl groups, which enhances the chemical stability of the material, while glycerol provides "soft" crosslinking/plasticization through interactions with carboxyl groups and promotes structural densification [6]. This determines the prospects of xanthan-based gels not only for bioremediation applications but also for probiotic systems, where the matrix functions as a carrier for active microorganisms.

Another example demonstrates that XG, in combination with polydimethylsiloxane, promotes the formation of a thicker biofilm of Acidithiobacillus ferrooxidans; with zeolite, it supports the survival of Pseudomonas cells during storage and soil application; in κ-carrageenan/Ca-alginate granules, it enhances stability in wastewater; in PVA/XG systems, it reduces cell leakage and accelerates denitrification or phenol degradation, as well as promotes the biodegradation of naproxen.

Study [37] also summarizes approaches to the encapsulation of plant probiotic bacteria (PGPB)–Bacillus, Pseudomonas, Azospirillum, Rhizobium, Enterobacter–using XG as a matrix polymer. Microcapsule formation is carried out by ionic gelation, emulsion-droplet technology, and polyelectrolyte complexation. Xanthan is used either as an independent matrix or in combination with alginate, chitosan, pectin, starch, and cellulose derivatives; crosslinking occurs via Ca^{2+}, Mg^{2+} ions or electrostatic interactions in systems such as "XG–CS," resulting in the formation of a stable hydrogel network [37].

Moreover, within the concept of natural superabsorbent polymers in agriculture, XG is considered a multifunctional biopolymer capable of forming hydrophilic three-dimensional networks with high water retention capacity. It has been shown that XG is effectively applied for soil stabilization, regulation of porous structure, and enhancement of moisture retention, which directly affects plant growth and survival. In addition, XG is used as an encapsulating agent in seed coatings and biocontrol delivery systems, ensuring the preservation of microbial viability and prolonged interaction with the plant environment. The ability of XG to immobilize heavy metal ions in soils through sorption mechanisms has also been established [38].

In study [39], the immobilization of Lactobacillus harbinensis cells was described with the aim of enhancing the efficiency of antifungal metabolite production. Gellan was used as a modifying agent, which reduced cell leaching and contributed to the accumulation of metabolites within the local gel volume, thereby increasing the overall antimycotic efficiency of the system. It was shown that cells immobilized in an XG-based carrier produce a complex of organic acids (in particular lactic, acetic, and hexanoic acids), which act synergistically to inhibit fungal growth.

In study [40], the immobilization of Bifidobacterium animalis subsp. lactis Bb12 in a gellan–xanthan matrix was investigated. An important observation is that probiotic cultures remain metabolically active and produce organic acids, particularly acetic acid, which, upon accumulation to critical levels, inhibits the growth of acid-sensitive bacteria. However, the polysaccharide carrier is unable to inhibit the action of these organic acids.

Another system, based on XG–CS with immobilized Bifidobacterium bifidum BB01, is described in [41]. The authors highlight the formation of single-layer (XG–CS) and double-layer (XG–CS–XG) microcapsules. The formation of a double layer (XG–CS–XG) provides an additional diffusion barrier, where the outer XG layer stabilizes the structure and regulates mass transfer. The protective mechanism of such capsules against the aggressive gastric environment is realized through restriction of proton and bile salt diffusion into the inner volume of the capsule, as well as through the pH-responsive behavior of the polymer network: in acidic conditions, structural densification occurs, whereas at pH > 8 (simulating intestinal conditions), swelling followed by controlled cell release (targeted delivery) takes place. It should be noted that single-layer systems (XG–CS) shell.

In study [42], bifidobacterial cells were immobilized in gellan–xanthan hydrogel beads to enhance their acid resistance and ensure effective delivery within the gastrointestinal tract, particularly in yogurt formulations. It was established that the incorporation of XG improves the morphology and mechanical stability of the particles and provides significantly higher cell survival even at pH 1.5.

The authors of [43] also investigated xanthan-based hydrogel matrices modified with alginate and inulin, which increase system viscosity, limit oxygen penetration, buffer acid stress, and improve the mechanical stability of microcapsules. This ensures the preservation of probiotic viability during processing, storage in beverages, and gastrointestinal transit, as well as their controlled release.

The results obtained in [44] on the development of a matrix with immobilized multistrain probiotics (*Bacillus coagulans* and *Lactobacillus reuteri*) demonstrate that resistant dextrin and XG form a composite RD/XG gel, yielding an MRX system for oral administration. The synergy of the components ensures the formation of a dense gel network, which enhances acid resistance, bioadhesion, and prolonged retention of probiotics in the colon. As a result, intestinal colonization is enhanced, the production of short-chain fatty acids and mucin is stimulated, contributing to the restoration of barrier function and reduction of radiation-induced damage.

In study [45], the immobilization of *Pseudomonas* sp. ADP cells was investigated by their deposition onto natural zeolite with the addition of XG as an auxiliary polymer component of the matrix. It was established that such a composition provides enhanced stability and survival of microorganisms during storage at 25 °C (up to 10 weeks), as well as the preservation of functional activity in atrazine degradation, indicating the role of XG in stabilizing cells within the heterogeneous "zeolite–biopolymer" system.

From the above, it can be concluded that the encapsulation of microorganisms in XG-based carriers occurs with preservation of their metabolic activity, increased survival under abiotic stress factors, and provision of controlled cell release.

5. *Immobilization of other objects: implemented cases and prospects.*Along with the considered systems for immobilization of pharmaceuticals, enzymes, and microorganisms, it is appropriate to analyze other types of systems in which the "polymer matrix – (modifier) – immobilized object" framework is realized. In such systems, XG performs the function of a polyanionic matrix whose structural and rheological characteristics are regulated through the introduction of modifying agents, including metal ions, low-molecular-weight compounds, or complementary polymers, thereby enabling control over binding mechanisms and mass transfer.

This category includes systems for the immobilization of antioxidants, adsorption of soil and wastewater pollutants, as well as the formation of rheologically controlled compositions for additive manufacturing technologies. The distinguishing feature of such systems lies in the variation of the nature of the immobilized object and the dominant types of interactions (ionic, coordination, sorption), which justifies their classification as a separate direction within this study. Their investigation enables a systematic description of the interrelation within the aforementioned system and expands the understanding of XG as a universal polymer platform.

Gallic acid in meat systems functions as an antioxidant. However, at high concentrations, it interacts with myofibrillar proteins through hydrogen bonding and hydrophobic associations, leading to protein aggregation and deterioration of functional properties. In this regard, the use of hydrocolloid matrices is appropriate for regulating protein–polyphenol interactions. Study [46] demonstrated that the incorporation of XG into the "myofibrillar proteins/gallic acid" (MP/GA) system reduces the degree of protein aggregation due to competitive interactions and spatial separation of components. This is accompanied by a decrease in aggregate size and surface hydrophobicity, while promoting the formation of a more ordered gel structure. As a result, the gel-forming and emulsifying properties of the system are improved, water-holding capacity and emulsion stability are enhanced, which is conditioned the hydrophilicity, charge, and ability of XG to modify the rheological properties of the medium.

In study [47], cryogel systems based on XG were developed as matrices for the immobilization of anthocyanin-containing berry extracts (from blueberry, blackcurrant, and blackberry) aimed at creating pH-sensitive indicators of fish freshness. Carrier formation was performed using two approaches: physical crosslinking through freeze–thaw cycles in the XG/PVA/anthocyanin extract system, and dual crosslinking, where cryogel formation was combined with preliminary chemical crosslinking of the XG matrix prior to extract incorporation. The authors associate anthocyanin stabilization within the cryogel network with noncovalent interactions, primarily hydrogen bonding, as well as π–π interactions and the formation of

hydrophobic microdomains within the matrix. Structural analysis confirmed the incorporation of the extract into the xanthan-based cryogel, while FTIR spectroscopy revealed the involvement of hydrogen bonds in the retention of bioactive compounds. The obtained cryogels exhibited prolonged colorimetric stability, sensitivity to volatile amines, and pronounced color changes during spoilage of Berlin carp, confirming the prospects xanthan-based cryogels as functional matrices for the immobilization of natural pH-sensitive pigments in intelligent food packaging.

Cryogel systems were also investigated in [48], where the authors demonstrated that porous cryogel films based on XG modified with polyvinyl alcohol, obtained via repeated freeze–thaw cycles, are capable of physically immobilizing (entrapping) red grape pomace (RGP) as a natural source of antioxidant and antimicrobial compounds. It was shown that system stability is primarily determined by crystalline regions of PVA formed during freeze–thaw cycles. The filling of pores with RGP limited water access to the cavities, imparting pronounced antioxidant and antimicrobial properties to the films.

In the study [49], blueberry anthocyanins were immobilized in microcapsules formed within a xanthan-based carrier modified with carboxymethyl starch (CMS). It was shown that XG in combination with CMS acts as a structural component of the microcapsule shell, providing high encapsulation efficiency, enhanced thermal stability, and improved storage stability. FTIR and solid-state ^{13}C NMR analyses revealed specific interactions between anthocyanins and the CMS/XG polymer network, interpreted as the formation of a crosslinked structure. In vitro studies demonstrated that anthocyanins are retained in the gastric environment and released in the intestine, indicating that the carrier ensures protection of bioactive compounds and enables their controlled release.

Pickering emulsions stabilized by composite particles of whey protein hydrolysate and XG (WPH–XG) were used as carriers for the encapsulation and stabilization of resveratrol. The particles were formed via co-assembly of WPH and XG at different pH values and component ratios, after which they were applied as solid emulsifiers for stabilizing oil-in-water systems. It was shown that XG plays a key role in the formation of cohesive and viscoelastic interfacial films due to its interaction with peptides via hydrogen bonding and electrostatic forces, which enhances emulsion stability and prevents droplet coalescence. Additionally, it was established that resveratrol promotes protein adsorption at the phase interface and contributes to strengthening of the interfacial structure, while rheological and NMR studies confirm the formation of a gel-like system with enhanced water binding [50].

In the study of emulsion gels based on XG and sodium stearoyl lactylate (SSL), it was demonstrated that immobilization of the hydrophobic phase is realized through physical entrapment of oil droplets within the three-dimensional xanthan gel network, while SSL stabilizes them at the phase interface, preventing coalescence. In contrast, in systems based on complexation of XG with oppositely charged polymer components (e.g., XG–DD), retention of bioactive compounds occurs at the nanoscale due to electrostatic interactions and the formation of polyelectrolyte complexes. Thus, while emulsion gels are dominated by the mechanism of spatial (structural) confinement of the dispersed phase, nanoparticle systems exhibit molecularly driven immobilization, which determines differences in the scale of organization, stability, and functional properties of the systems [51].

In the study [52], it was shown that the efficiency of β-carotene encapsulation is determined not only by the presence of an XG-based matrix but also by the formation of internal hydrophobic domains associated with ethyl groups of diethylaminoethyl dextran, which act as “micro-reservoirs” for hydrophobic molecules. An important distinction is also the detailed elucidation of mucoadhesion mechanisms: in addition to electrostatic attraction between positively charged nanoparticles and mucin, the contribution of nonelectrostatic interactions (hydrogen bonding, physical entrapment), characteristic of XG, was established, explaining the preservation of adhesion even in negatively charged systems.

The authors of [53] presented approaches to the application of XG in various fields related to human life and health. This review attempts to explore the potential of XG in 3D printing for pharmaceutical and biomedical applications. Alongside the analysis of different 3D printing methods in tissue engineering and drug delivery, particular attention is paid to physicochemical and rheological properties, as well as to how XG can be incorporated into various formulations, such as tablets, capsules, and hydrogels, to modulate drug release and mucoadhesion. In addition to its limitations, challenges, and prospects, the review also emphasizes the use of

scaffolds, bioinks, and hybrid polymers in 3D printing formulations for regenerative medicine [53].

The following section presents research results related to wastewater treatment techniques for dye removal using immobilization principles in xanthan-based carriers. Thus, in study [54], a crosslinked hydrogel nanocomposite based on XG, poly(AA-co-AMPSA), and functionalized graphene oxide was developed and applied for the removal of the cationic dye crystal violet from aqueous solutions. It was shown that electrostatic interactions occur between the ($–COO^-$, –OH) groups of the carrier and the dye. In study [55], the development of a novel antibacterial nanoadsorbent based on XG and SiO_2 nanoparticles is described; it was obtained via ultrasonic treatment followed by crosslinking with 1-vinylimidazole and applied for the removal of the cationic dye malachite green from aqueous solutions, while simultaneously inhibiting the growth of E. coli and S. aureus. The XG structure contributed to uniform dispersion of SiO_2 nanoparticles through possible electrostatic interactions and hydrogen bonding.

A composite system based on XG and konjac glucomannan ensures effective immobilization of mucin through the formation of a rigid three-dimensional network that physically entraps gastric mucosal components and limits their mobility; at an XG content exceeding 50 %, a transition to an entropy-driven network retention mechanism occurs, promoting the formation of a stable mucoadhesive layer capable of prolonged retention of gastric contents. Such mucin immobilization not only enhances the adhesive strength of the system but also ensures prolonged retention of the food substrate in the stomach, slowing its evacuation and providing sustained mechanical stretching of the gastric walls, which activates satiety signals. As a result, an effect of faster onset and prolonged maintenance of satiety is achieved, opening prospects for the use of such systems as functional food ingredients for appetite control and body weight reduction [56].

Results and Discussion

As evidenced by the generalized analytical results, the immobilization of bioactive compounds is a key technological approach that ensures enhanced stability, prolongation of functional activity, and the possibility of controlled performance under specified environmental conditions.

In study [2], a classification of enzyme immobilization methods into chemical and physical categories is presented. At the same time, our analysis of empirical data from the reviewed sources allowed us to expand the scope of this approach by extending it to other immobilization objects, including non-biological ones.

Chemical immobilization involves the formation of strong bonds between the object and the matrix (covalent or ionic), which ensures high stability of the formed system; the main approaches include covalent bonding between amide, imine, or disulfide groups and the functional groups of the system, as well as the formation of three-dimensional polymer networks as a result of multipoint covalent interactions (crosslinking). Physical immobilization is realized through the formation of weak noncovalent interactions (hydrogen bonding, van der Waals forces, hydrophobic interactions, dipole–dipole interactions), as well as through mechanical entrapment of objects within the polymer matrix. Table 1 was developed (author's compilation based on [2]), which presents the characteristics of the main types of immobilization in XG-based hydrogel matrices.

Table

Main types of immobilization in xanthan-based carrier systems and their characteristics

Type	Mechanism of implementation	Types of interactions	Role of xanthan gum
Adsorptive	Attachment of objects on the surface or in the near-surface layers of the carrier	Electrostatic, hydrogen bonding, van der Waals forces	Acts as a polyanionic surface with carboxyl and hydroxyl groups
Ion-exchange	Binding of cations or positively charged functional groups of a modifier or object via ionic centers of the carrier	Ionic, coordination	Carboxyl and pyruvate groups of glucuronic acid form binding centers for positively charged particles
Affinity	Selective binding via specific functional groups or ligand centers	Coordination, chelation, specific ligand–metal or ligand–biomolecule interactions	Modified xanthan (with thiol, amino groups or introduced ligands, e.g., N-acetylcysteine) creates active binding sites
Entrapment	Spatial confinement of the object within the pores of the carrier without chemical bonding	Physical retention, hydrogen bonding, weak electrostatic interactions	Forms a three-dimensional hydrogel network with controlled porosity and swelling degree

Encapsulation	Incorporation of the object into the volume of the carrier with formation of micro-/nanostructures	Combined (physical retention, ionic and hydrogen bonding)	Acts as a matrix polymer or copolymer (e.g., with alginate, chitosan, gellan, guar, etc.)
Covalent (as a special case of affinity)	Attachment of the object to the carrier or modifier via covalent bonding	Covalent bonds (amide, ester, disulfide)	Modified xanthan (thiolated, esterified)

Thus, summarizing the data presented in Table, it is possible to distinguish the main mechanisms of immobilization of objects in polymer matrices based on or involving XG, taking into account the nature of interactions between the object and the carrier. It has been established that physical mechanisms are realized through noncovalent interactions or spatial entrapment within the structure (pores) of the hydrogel, whereas chemical approaches are associated with the formation of ionic or covalent bonds between the functional groups of the carrier and the object.

The immobilization processes presented in the table reflect various modes of fixation of objects within the polymer network of the carrier – from surface adsorption to incorporation into the bulk of the polymer matrix or the formation of chemically bonded systems–which directly affects the degree of retention, diffusion capability, and the nature of interaction with environmental components.

Conclusions

The generalization of the results of the presented analytical review indicates that the development of xanthan-based immobilization systems forms a universal platform for the creation of functional materials, particularly for medical and environmental applications. It has been established that the efficiency of such systems is conditioned by the presence of carboxyl, acetyl, and pyruvate groups in the XG structure, which enable ionic, coordination, and hydrogen interactions with both abiotic and biotic immobilized compounds. Among these, ionic interaction (particularly between $–COO^-$ groups of XG and metal cations or protonated functional groups of bioactive substances) is the key mechanism governing the retention and stabilization of components within the hydrogel matrix, as it not only ensures immobilization of positively charged objects but also contributes to the formation of a spatially organized porous structure capable of physically retaining other molecules within the polymer network.

In pharmaceutical systems, this enables prolonged release, enhanced bioavailability, reduction of therapeutic doses, and minimization of side effects. Of particular interest are magnetically responsive composite materials (notably those containing Fe_3O_4 nanoparticles), which combine the properties of an XG-based matrix with the capability for controlled transport and localized delivery of active substances under the influence of an external magnetic field.

It is also necessary to emphasize the mechanisms of ionic binding, which determine the high efficiency of XG-based systems in environmental remediation technologies, particularly in the removal of heavy metal ions (Pb^{2+}, Cd^{2+}, Cu^{2+}, Cr^{3+}) from wastewater and contaminated soils. In such systems, XG acts as a polyanionic sorbent or as a component of polyelectrolyte complexes, enabling sorption through electrostatic interactions, ion exchange, and chelation. The combination of XG with other polymeric or inorganic components (metal cations) allows the formation of hybrid adsorption materials with enhanced capacity, selectivity, and regenerable sorption activity.

At the same time, the practical implementation of such systems is complicated by the need for extensive and resource-intensive experimental studies for each new composition. In this context, quantum-chemical modeling is considered an effective tool for preliminary prediction of the structural and energetic characteristics of "xanthan–(modifier)–immobilized object" systems, particularly for determining stable conformations, the nature of intermolecular interactions, and the localization of active binding sites. However, the absence of a unified protocol for conducting such studies limits the possibilities for systematization and scaling of the obtained results.

In this regard, a promising direction is the application of quantum-chemical calculations to simplified structural fragments of XG with subsequent modeling of typical ionic and coordination interactions and extrapolation of the obtained data to complex hydrogel and composite systems, including supramolecular structures involving peptides, proteins, and enzymes. This approach would significantly optimize the design of innovative functional materials, both for controlled drug delivery and for efficient environmental remediation.

References

[1] Metin, A. Ü., Horzum, N., Dağcı, A., Savaş, A. T. (2025). Xanthan gum-based Magnosorbent: A selective, rapid, and high-capacity adsorbent for pH-tolerant methylene blue removal from complex pollutant systems. *International Journal of Biological Macromolecules, 328*(Pt 2), 147640. https://doi.org/10.1016/j.ijbiomac.2025.147640

[2] Prabhakar, T., Giaretta, J., Zulli, R., Rath, R. J., Farajikhah, S., Talebian, S., Dehghani, F. (2025). Covalent immobilization: A review from an enzyme perspective. *Chemical Engineering Journal, 503*, 158054. https://doi.org/10.1016/j.cej.2024.158054

[3] Okovytyy, S. I., Kondratiuk, N. V., Polyvanov, Y. A. (2025). Xanthan: Research into innovative modification strategies and industrial applications. *Journal of Chemistry and Technologies, 33*(4), 1232–1251. https://doi.org/10.15421/jchemtech.v33i4.350021

[4] Kang, M., Oderinde, O. K., Liu, S., Huang, Q., Ma, W., Yao, F., Fu, G. (2019). Characterization of Xanthan gum-based hydrogel with Fe^{3+} ions coordination and its reversible sol-gel conversion. *Carbohydrate Polymers, 203*, 139–147. https://doi.org/10.1016/j.carbpol.2018.09.044

[5] Jaipal, A., Pandey, M. M., Abhishek, A., Vinay, S., Charde, S. Y. (2013). Interaction of calcium sulfate with xanthan gum: Effect on in vitro bioadhesion and drug release behavior from xanthan gum based buccal discs of buspirone. *Colloids and Surfaces B: Biointerfaces, 111*, 644–650. https://doi.org/10.1016/j.colsurfb.2013.06.052

[6] Dzionek, A., Wojcieszyńska, D., & Guzik, U. (2022). Use of xanthan gum for whole cell immobilization and its impact in bioremediation - a review. *Bioresource Technology, 351*, 126918. https://doi.org/10.1016/j.biortech.2022.126918

[7] Dário, A. F., Hortêncio, L. M., Sierakowski, M. R., Neto, J. C. Q., Petri, D. F. S. (2011). The effect of calcium salts on the viscosity and adsorption behavior of xanthan. *Carbohydrate Polymers, 84*(1), 669–676. https://doi.org/10.1016/j.carbpol.2010.12.047

[8] Ko, M.-S., Jeon, Y.-J., Kim, K.-W. (2022). Novel application of xanthan gum-based biopolymer for heavy metal immobilization in soil. *Journal of Environmental Chemical Engineering, 10*(5), 108240. https://doi.org/10.1016/j.jece.2022.108240

[9] Balíková, K., Farkas, B., Matúš, P., Urík, M. (2022). Prospects of biogenic xanthan and gellan in removal of heavy metals from contaminated waters. *Polymers, 14*(23), 5326. https://doi.org/10.3390/polym14235326

[10] Ahmad, R., Mirza, A. (2018). Application of xanthan gum/n-acetyl cysteine modified mica bionanocomposite as an adsorbent for the removal of toxic heavy metals. *Groundwater for Sustainable Development, 7*, 101–108. https://doi.org/10.1016/j.gsd.2018.03.010

[11] Rahmatpour, A., Alizadeh, A. H. (2024). Biofilm hydrogel derived from physical crosslinking (self-assembly) of xanthan gum and chitosan for removing Cd^{2+}, Ni^{2+}, and Cu^{2+} from aqueous solution. *International Journal of Biological Macromolecules, 266*(Pt 2), 131394. https://doi.org/10.1016/j.ijbiomac.2024.131394

[12] 12. He, S., Chen, J., Wang, X., Wang, X., Li, P., & Zhang, Y. (2024). Green preparation of regenerable biohybrids with xanthan gum-stabilized biogenic mackinawite nanoparticles for efficient treatment from high-concentration uranium wastewater. *Bioresource Technology, 408*, 131104. https://doi.org/10.1016/j.biortech.2024.131104

[13] Ghubayra, R., Mousa, I., Madkhali, M. M. M., Alaghaz, A. M. A., & Hassan, A. F. (2024). Fabrication and characterization of xanthan gum nanofibers reinforced with thiosemicarbazide: adsorption of Pb^{2+} from an aqueous medium. *RSC Advances*, 14, 37859–37870. https://doi.org/10.1039/d4ra06364c

[14] Ribeiro, M., Boudoukhani, M., Belmonte-Reche, E., Genicio, N., Sillankorva, S., Gallo, J., Rodríguez-Abreu, C., Moulai-Mostefa, N., Bañobre-López, M. (2021). Xanthan-Fe_3O_4 nanoparticle composite hydrogels for non-invasive magnetic resonance imaging and magnetically assisted drug delivery. *ACS Applied Nano Materials, 4*(8), 7712–7725. https://doi.org/10.1021/acsanm.1c00932

[15] Bueno, P. V. A., Hilamatu, K. C. P., Carmona-Ribeiro, A. M., Petri, D. F. S. (2018). Magnetically triggered release of amoxicillin from xanthan/Fe_3O_4/albumin patches. *International Journal of Biological Macromolecules, 115*, 792–800. https://doi.org/10.1016/j.ijbiomac.2018.04.119

[16] Koyuncu, I., Yavuzturk Gul, B., Esmaeili, M. S., Yildiz, E., Koseoglu-Imer, D. Y., & Koyuncu, I. (2022). Modification of PVDF membranes by incorporation Fe_3O_4@Xanthan gum to improve anti-fouling, anti-bacterial, and separation performance. *Journal of Environmental Chemical Engineering, 10*(3), 107784. https://doi.org/10.1016/j.jece.2022.107784

[17] Peng, X., Xu, F., Zhang, W., Wang, J., Zeng, C., Niu, M., & Chmielewská, E. (2014). Magnetic Fe_3O_4@silica–xanthan gum composites for aqueous removal and recovery of Pb^{2+}. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 443, 27–36. https://doi.org/10.1016/j.colsurfa.2013.10.062

[18] Singh, N. S. S., Gataa, I. S., Saleh, L. H., Jabbar, A. H., Al-Ahmed, A. (2026). Design and immobilized gold nanoparticles into the chitosan-xanthan gum polymers as a novel catalyst for efficient nitroarenes reduction in water. *Journal of Organometallic Chemistry, 1043*, 123902. https://doi.org/10.1016/j.jorganchem.2025.123902

[19] Inamuddin, A. M. I. (2018). Xanthan gum/titanium dioxide nanocomposite for photocatalytic degradation of methyl orange dye. *International Journal of Biological Macromolecules, 124*, 1–10. https://doi.org/10.1016/j.ijbiomac.2018.10.064

[20] Virzì, N. F., Diaz-Rodriguez, P., et al. (2025). Combining antibacterial and wound healing features: Xanthan gum/guar gum 3D-printed scaffold tuned with hydroxypropyl-β-cyclodextrin/thymol and Zn^{2+}. *Carbohydrate Polymers, 351*, 123069. https://doi.org/10.1016/j.carbpol.2024.123069

[21] Yahoum, M. M., Toumi, S., Tahraoui, H., Lefnaoui, S., Kebir, M., Amrane, A., Assadi, A. A., Zhang, J., & Mouni, L. (2023). Formulation and evaluation of xanthan gum microspheres for the sustained release of metformin hydrochloride. *Micromachines, 14*(3), 609. https://doi.org/10.3390/mi14030609

[22] Laffleur, F., Michalek, M. (2017). Modified xanthan gum for buccal delivery–A promising approach in treating sialorrhea. *International Journal of Biological Macromolecules, 102*, 1250–1256. https://doi.org/10.1016/j.ijbiomac.2017.04.123

[23] Mikac, U., et al. (2019). Dynamics of water and xanthan chains in hydrogels studied by NMR relaxometry and their influence on drug release. *International Journal of Pharmaceutics, 563*, 373–383. https://doi.org/10.1016/j.ijpharm.2019.04.014

[24] Chang, Y.-T., Wang, S.-H., Tsai, M.-S., Hsieh, C. W., & Lee, H.-B. (2019). Preparation and physicochemical and cytocompatibility analyses of a magnetic polymer colloid of xanthan gum-chitosan/nickel nanowires. *Results in Physics, 13*, 102224. https://doi.org/10.1016/j.rinp.2019.102224

[25] Zheng, M., Lian, F., Xiong, Y., Liu, B., Zhu, Y., Miao, S., Zhang, L., Zheng, B. (2019). The synthesis and characterization of a xanthan gum-acrylamide-trimethylolpropane triglycidyl ether hydrogel. *Food Chemistry, 272*, 574–579. https://doi.org/10.1016/j.foodchem.2018.08.083

[26] Wang, B., Han, Y., Lin, Q., Liu, H., Shen, C., Nan, K., & Chen, H. (2016). In vitro and in vivo evaluation of xanthan gum–succinic anhydride hydrogels for the ionic strength-sensitive release of antibacterial agents. *Journal of Materials Chemistry B, 4*, 1853–1861. https://doi.org/10.1039/C5TB02046H

[27] Huang, S., An, S., Ramesh Kannan, P., Wahab, A., Alamgir, Ali, S., Xiaoqing, L., Suhail, M., Iqbal, M. Z., & Kong, X. (2025). Development and characterization of biodegradable antibacterial hydrogels of xanthan gum for controlled ciprofloxacin release. *International Journal of Biological Macromolecules, 309*(Pt 1), 142637. https://doi.org/10.1016/j.ijbiomac.2025.142637

[28] Layek, B. (2024). A comprehensive review of xanthan gum-based oral drug delivery systems. *International Journal of Molecular Sciences, 25*(18), 10143. https://doi.org/10.3390/ijms251810143

[29] Sharma, A., Thatai, K. S., Kuthiala, T., Singh, G., Arya, S. K. (2021). Employment of polysaccharides in enzyme immobilization.

Reactive and Functional Polymers, 167, 105005. https://doi.org/10.1016/j.reactfunctpolym.2021.105005

[30] Prabhakar, T., Giaretta, J., Zulli, R., Rath, R. J., Farajikhah, S., Talebian, S., Dehghani, F. (2025). Covalent immobilization: A review from an enzyme perspective. *Chemical Engineering Journal, 503*, 158054. https://doi.org/10.1016/j.cej.2024.158054

[31] Method of immobilizing biochemically active substance with xanthan gum (1990). Method of immobilizing biochemically active substance with xanthan gum. US Patent US4954443A.

[32] Xu, W., Lou, Y., Xu, B., Li, Y., Xiong, Y., & Jing, J. (2018). Mineralized calcium carbonate/xanthan gum microspheres for lysozyme adsorption. *International Journal of Biological Macromolecules, 120*(Pt B), 2175–2179. https://doi.org/10.1016/j.ijbiomac.2018.09.041

[33] Ribeiro, E. S., Machado, B. R., de Farias, B. S., Han, L. H., dos Santos, L. O., Duarte, S. H., Cadaval Junior, T. R. S., de Almeida Pinto, L. A., Diaz, P. S. (2025). Bi-layer nanocapsules based on chitosan and xanthan gum for lipase immobilization. *Journal of Molecular Liquids, 434*, 128031. https://doi.org/10.1016/j.molliq.2025.128031

[34] Tapdigov, S. Z. (2021). The bonding nature of the chemical interaction between trypsin and chitosan based carriers in immobilization process depend on entrapped method: A review. *International Journal of Biological Macromolecules, 183*, 1676–1696. https://doi.org/10.1016/j.ijbiomac.2021.05.059

[35] Dumitriu, S., Chornet, E. (1997). Immobilization of xylanase in chitosan–xanthan hydrogels. *Biotechnology Progress, 13*(5), 539–545. https://doi.org/10.1021/bp970059i

[36] Sheikhzadeh, S., Khaledabad, M. A., Almasi, H. (2025). In situ growth of β-galactosidase-manganese hybrid nanoflower on polycaprolactone/xanthan electrospun nanofibers: A novel nanobiocatalyst for efficient lactose hydrolysis. *Journal of Agriculture and Food Research, 22*, 102058. https://doi.org/10.1016/j.jafr.2025.102058

[37] Hassanisaadi, M., Vatankhah, M., Kennedy, J. F., Rabiei, A., Saberi Riseh, R. (2025). Advancements in xanthan gum: A macromolecule for encapsulating plant probiotic bacteria with enhanced properties. *Carbohydrate Polymers, 348*(Pt A), 122801. https://doi.org/10.1016/j.carbpol.2024.122801

[38] Dingley, C., Cass, P., Adhikari, B., & Daver, F. (2024). Application of superabsorbent natural polymers in agriculture. *Journal of Plastic Film & Sheeting, 40*(1), 3–45. https://doi.org/10.1177/20412479231226166

[39] Belguesmia, Y., Rabesona, H., Mounier, J., Pawtowsky, A., Le Blay, G., Barbier, G., Haertlé, T., & Chobert, J.-M. (2014). Characterization of antifungal organic acids produced by Lactobacillus harbinensis K.V9.3.1Np immobilized in gellan–xanthan beads during batch fermentation. *Food Control, 36*(1), 205–211. https://doi.org/10.1016/j.foodcont.2013.08.028

[40] Jalili, H., Razavi, S. H., & Amrane, A. (2011). Unstructured model for free and immobilized cell culture of Bifidobacterium animalis. *Biochemical Engineering Journal, 58-59*, 120–128. https://doi.org/10.1016/j.bej.2011.09.007

[41] Chen, L., Yang, T., Song, Y., Shu, G., Chen, H. (2017). Effect of xanthan-chitosan-xanthan double layer encapsulation on survival of Bifidobacterium BB01 in simulated gastrointestinal conditions, bile salt solution and yogurt. *LWT – Food Science and Technology, 81*, 274–280. https://doi.org/10.1016/j.lwt.2017.04.005

[42] Sun, W., Griffiths, M. W. (2000). Survival of bifidobacteria in yogurt and simulated gastric juice following immobilization in gellan–xanthan beads. *International Journal of Food Microbiology, 61*(1), 17–25. https://doi.org/10.1016/S0168-1605(00)00327-5

[43] Ramisetti, P., Muchahary, S. (2025). Enhancing probiotic viability in synbiotic beverages: Functional role of xanthan gum. *Food and Humanity, 5*, 100943. https://doi.org/10.1016/j.foohum.2025.100943

[44] Wang, M., Sun, R., Zeng, L., Du, S., Fang, Y., Zhuang, B., Yuan, B., Jin, Y. (2026). Resistant dextrin/xanthan gum gels protect probiotics for application to ionizing radiation shielding. *Food Research International, 227*, 118191. https://doi.org/10.1016/j.foodres.2025.118191

[45] Hong, H., Churchman, J., Gu, Y., Yin, K., Wang, C. (2012). Kaolinite–smectite mixed-layer clays in the Jiujiang red soils and their climate significance. *Geoderma*, 173-174, 75–83. https://doi.org/10.1016/j.clay.2011.12.006

[46] Chen, J., Wang, S., Ji, Z., Yi, X., Guo, J., Jin, G., Wu, Z. (2025). Inhibition mechanisms of xanthan gum on high-dose gallic acid-induced functional deterioration of myofibrillar protein: Focusing on gelling and emulsification behaviors. *Carbohydrate Polymers, 368*(1), 124096. https://doi.org/10.1016/j.carbpol.2025.124096

[47] Raschip, I. E., Platon, I.-V., Fifere, N., Darie-Nita, R.-N., Dinu, M. V. (2025). Stabilization of anthocyanins in xanthan-based systems for synergistic cryogels with enhanced physicochemical and biological properties for visual freshness monitoring of Prussian carp (Carassius gibelio). *Food Hydrocolloids, 168*, 111566. https://doi.org/10.1016/j.foodhyd.2025.111566

[48] Raschip, I. E., Fifere, N., Varganici, C.-D., & Dinu, M. V. (2020). Development of antioxidant and antimicrobial xanthan-based cryogels with tuned porous morphology and controlled swelling features. *International Journal of Biological Macromolecules, 156*, 608–620. https://doi.org/10.1016/j.ijbiomac.2020.04.086

[49] Cai, X., Du, X., Cui, D., Wang, X., Yang, Z., Zhu, G. (2019). Improvement of stability of blueberry anthocyanins by carboxymethyl starch/xanthan gum combinations microencapsulation. *Food Hydrocolloids, 91*, 238–245. https://doi.org/10.1016/j.foodhyd.2019.01.034

[50] Li, Y., Yin, Y., Jia, N., Yu, J., Wang, L., & Peng, X. (2026). Interfacial structuring and antioxidant enhancement of resveratrol-loaded Pickering emulsions stabilized by whey protein hydrolysate–xanthan gum complexes. *International Journal of Biological Macromolecules*, *343*(Pt 1), 150412. https://doi.org/10.1016/j.ijbiomac.2026.150412

[51] Liu, C., Li, Y., Liang, R., Sun, H., Wu, L., Yang, C., Liu, Y. (2023). Development and characterization of ultra-stable emulsion gels based on synergistic interactions of xanthan and sodium stearoyl lactylate. *Food Chemistry, 400*, 133957. https://doi.org/10.1016/j.foodchem.2022.133957

[52] Pispas, I., Pavlova, E., Slouf, M., Papagiannopoulos, A. (2025). Xanthan-based nanocomplexes: modulating colloidal properties, model compound encapsulation and mucoadhesion via diethylaminoethyl dextran. *International Journal of Biological Macromolecules, 329*(Pt 1), 147766. https://doi.org/10.1016/j.ijbiomac.2025.147766

[53] Patel, R., Tosif, M. M., Alsaidan, O. A., Prajapati, B. (2025). Xanthan gum-based formulations for additive manufacturing: Scientific developments in drug delivery and biomedical applications. *Carbohydrate Polymers, 366,* 123914. https://doi.org/10.1016/j.carbpol.2025.123914

[54] Mittal, H., Al Alili, A., Morajkar, P.P., Alhassan, S.M. (2021). Graphene oxide crosslinked hydrogel nanocomposites of xanthan gum for the adsorption of crystal violet dye. *Journal of Molecular Liquids, 323*, 115-034. https://doi.org/10.1016/j.molliq.2020.115034

[55] Abu Elella, M. H., Goda, E. S., Gamal, H., El-Bahy, S. M. (2021). Green antimicrobial adsorbent containing grafted xanthan gum/SiO_2 nanocomposites for malachite green dye. *International Journal of Biological Macromolecules, 191*, 385–395. https://doi.org/10.1016/j.ijbiomac.2021.09.040

[56] Chen, W., Wang, X., Liang, H., Li, J., Li, B. (2026). Xanthan gum alters the mucosal adhesion performance of konjac glucomannan through an entropy loss-type network entrapment mechanism. *Food Chemistry, 510*, 148660. https://doi.org/10.1016/j.foodchem.2026.148660