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Review

Biomass of Microalgae and Other Phototrophic Microorganisms: Current Trends in Regulation of Its Accumulation and Application of Immobilized Forms

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Abstract

The current interest in microalgal biomass does not subside but continues to intensify due to the emergence of new trends in the use of this bioresource in various biotechnological and environmental processes. The rather slow growth rate of phototrophs compared to other microorganisms limits more active application of the biomass for various purposes. Stimulation of the Quorum Sensing formation in the cells due to the appearance of their own quorum molecules or those produced by other co-cultured microorganisms in the medium is one of the efficient approaches for overcoming this limitation. This review discusses the immobilization or co-immobilization of phototrophic cells with other microorganisms as an effective way to maintain accumulation of the target biomass for long-term period at improved rates. The 40% increase in the use of co-immobilized phototrophs for biomass obtaining and its use in wastewater treatment has been observed over the past five years. The level of investigations of co-immobilized microalgae cells is four times higher than that of the immobilized single cultures. Among the main trends in the new investigations of immobilized forms of microalgae, the predominant application of *Chlorella* genus cells in immobilized samples of individual cultures and the involvement of diatom microalgae and cyanobacteria, in addition to *Chlorella* cells, in co-immobilization with other microorganisms, was ascertained. The most significant increase in the rate of microalgal biomass accumulation uncovered in cases of co-immobilization of microalgae with bacteria. In several cases, in the presence of bacteria, co-immobilization has led to the emergence of new characteristics in microalgal cells (increased synthesis of pigments, polysaccharides, biofilm formation, etc.), which opens new directions for their further practical use as biopesticides, components of packaging and building materials, etc.

Keywords: Quorum Sensing; co-immobilization; sorption; growth rate; bacteria; fungi

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1. Introduction

The biotechnological interest in microalgae is enormous, as these organisms, being universal participants in many ecosystems, possess a unique natural potential due to their functions and biochemical characteristics [1–3]. They play an extremely important role in ecosystems, both as producers of organic substances from inorganic sources through photosynthesis during the light phase of their existence, and as consumers of organic substrates and their reducers during both the light and dark phases of their metabolism [2,3]. Thus, they exhibit multifunctionality in the biogeochemical cycling of matter within ecosys-

tems, and their natural potential has become an object of scientific study and applied technological development.

An analysis of the current state of science and the biotechnological use of microalgal biomass indicates that some research directions which were relevant and actively developed ten years ago are now gradually moving to the background [4]. For instance, not long ago, microalgae were considered as one of the best sources for obtaining lipids intended for transformation into biodiesel [5]. For that, cultivation conditions were selected to favor microalgal cells capable of accumulating biomass with metabolism shifted toward lipid formation. To stimulate this metabolic shift, microalgal cells were cultivated under stress conditions, depriving them of certain components in the nutrient medium. This led, for example, to an increase in the lipid fraction within the biochemical composition of the cells, but simultaneously reduced the overall biomass accumulation [6].

However, economic assessments of using microalgal biomass have shown that biofuel production is not economically viable unless the process simultaneously yields and commercializes a more valuable by-product [7,8]. This was due to the limited productivity of these microorganisms and the costs associated with their commercial cultivation and subsequent waste management. Nevertheless, a significant increase in the rate of target microalgal biomass accumulation could make the use of these phototrophic cells more commercially attractive [9,10]. For this reason, interest in methods of accelerating growth rates and biomass production over relatively short periods, while maintaining the metabolic activity of the accumulating cells, has sharply increased in recent years [11]. This is particularly important when using such cells in the purification of various media from different, including toxic, pollutants. Increasing the rate and scale of wastewater treatment becomes possible through the greater mass of biocatalysts, i.e., the microalgae cells themselves [12].

It should be noted that to achieve high concentrations of microalgal biomass, it is more appropriate to use optimized cultivation conditions with a defined composition of medium components, rather than using wastewater with a stochastic composition of carbon and nitrogen sources [13,14]. The reason lies in the fact that such waste streams may contain not only potential substrates for microalgae but also possible growth inhibitors (chemical or biotic), such as cadmium, mercury, or zinc, which do not promote the desired biomass accumulation. In addition, high concentrations of nitrogen-containing compounds and "nutritional imbalances" (the ratio between carbon and nitrogen) present in industrial wastewater can significantly slow down microalgal growth [15].

An analysis of approaches that ensure the desired acceleration of microalgal biomass production in sufficient quantities has shown that several possible strategies are currently under discussion:

(i) optimization of medium composition and cultivation regimes that enhance the efficiency of microalgae photosynthesis [16–19], as well as genetic modification of biomass producers to improve the performance of their photosynthetic apparatus [20];
(ii) stimulation of in situ synthesis or external introduction into the cultivation media of regulators of microalgal growth (phytohormones, molecules involved in the formation of so-called Quorum Sensing (QS) communication networks that regulate metabolic activity programs [21–23], and molecules that intensify gas-transfer processes [24], etc.);
(iii) utilization of microalgal cells in immobilized concentrated form as a dense inoculum for free-cell biomass accumulation [25,26];
(iv) co-immobilization of microalgae with other microorganisms, capable of exerting stimulating effects on the growth of phototrophs through their metabolites, including primarily QS molecules synthesized in situ [27,28].

It should be emphasized that immobilization of phototrophic microorganisms has recently received the greatest research attention. Immobilized forms of microalgae make it possible to simultaneously utilize several stimuli for biomass production (QS signaling, stabilized functioning through biofilm formation, higher tolerance to medium composition variations) while also expanding the cultivation conditions of such cells, including cases aimed at accumulating biomass with specific properties.

As the amount of the experimental data obtained by different researchers increased, it became obvious that interests of science are shifting from testing various immobilization methods applicable to phototrophic microorganisms to expanding the number of microalgae cells, whose potential is being studied in an immobilized state and may have practical significance. At the same time, the following scientific and practical issues appeared to be relevant:—what are the preferences in choosing phototrophs for immobilization based on their identified characteristics;—which properties of the resulting biomass when using immobilized phototrophic cells as inoculates are of interest for various purposes of its subsequent use;—which microalgae can be combined with other microorganisms in immobilized form for the purpose of accumulating their biomass, as far as it is expedient from a practical point of view. In this regard, this review focuses on the analysis of possible answers to the questions mentioned about the missing information and on the generalization of the main trends in the research and development of immobilized cells of phototrophic microorganisms, which can open new opportunities for applied achievements in their biotechnological use.

2. Molecular Regulators Providing Enhanced Biomass Accumulation of Phototrophic Microorganisms Used in Different Immobilized Forms

During the immobilization of cells, many of their properties are retained, in particular, the ability of the cells to respond to the presence of growth stimulators in the cultivation medium. In this case, newly formed daughter cells accumulate freely in the surrounding medium when the cells form part of biofilms, are included within porous gel structures, or are simply adsorbed onto the surface of various carriers. This is one of the key goals of using immobilized inoculum forms of microalgae [28]. In this regard, of particular interest is the analysis of molecular regulators that control the acceleration of microalgal growth, which have currently been identified and used, including for the formation of self-immobilizing forms of microalgae.

Research aimed at accelerating the growth of microalgal cells for their more active involvement in wastewater purification and the accumulation of desired metabolites [22] has confirmed general principles of growth stimulation shared by these microorganisms, bacteria, and terrestrial plants. These principles are based on the synthesis of phytohormones via the indole-3-pyruvic acid pathway and their use by microalgae as signaling molecules for intercellular communication [23,29]. The involvement of phytohormone molecules in stimulating the growth of various microalgal cells is actively applied during the cultivation of these microorganisms (Table 1 [24,27,30–42]).

Specific concentrations of these substances have been determined that promote the acceleration of phototrophic cell growth rather than its inhibition. In particular, for 3-indoleacetic acid, such “growth-promoting concentrations” for many microalgae were in the range of 10^{-7}–10^{-6} M [31,33]. These molecules accumulate in the medium as the number of microalgal cells increases. As a result, biofilms form, with the accumulating microalgal cells exhibiting phytohormone concentrations 1–2 orders of magnitude higher than those found in planktonic (free-floating) cells [22].

Table 1. Various molecules participating in the growth regulation of phototrophic microorganisms and QS functioning.

Phototrophic Microorganisms [Reference]	Regulators	Results of Regulators' Application
Chlorella sp. [27]	Indole-3-acetic acid, *N*-acyl-homoserine lactones	Growth and formation of stable granules with bacterial cells and their polysaccharides
Chlorella regularis [30]	Benzoic acid, salicylic acid	Increase in growth rate per 75% and 25% in presence of benzoic and salicylic acids, correspondently
Scenedesmus quadricauda [31]	2.4-epibrassinolid, 3-indoleacetic acid	Increase in growth rate (1.6–2.3-fold), lipid accumulation and carotenoid production
Nannochloropsis oceanica [32]	Abscisic acid, cytokinin	Increase in growth rate and lipid accumulation
Chlorella sorokiniana [33]	Indole-3-acetic acid	Increase in growth rate and biofilm formation
Geitlerinema sp. [34]	*N*-acyl-homoserine lactone	Growth and biofilm formation with anaerobic ammonium-oxidizing bacteria
Chlorella sp., *Anabaena* sp., *Navicula* sp. [35]	*N*-acyl-homoserine lactones	Improved biofilm formation with denitrifying and anaerobic ammonium-oxidizing bacteria for the removal of increased concentrations of ammonia (100 mg/L) from wastewater
Prorocentrum minimum, *Alexandrium tamarense*, *Chattonella marina*, *Prorocentrum donghaiense*, *Prorocentrum lima*, *Heterosigma akashiwo*, *Alexandrium streptosus*, *Karenia mikimotoi* [36]	*N*-(3-Oxodecanoyl)-L-homoserine lactone, *N*-Octanoyl-L-homoserine lactone, *N*-(3-Oxooctanoyl)-L-homoserine lactone	Active formation of biofilms with improved degradation activity in relation to β-dimethylmercaptopropionic acid
Isochrysis galbana [37]	Indole-3-acetic acid	Increased cell growth and biofilm formation
Isochrysis galbana [38]	Indole-3-acetic acid	Increase in microalgae growth and formation of microalgae-bacteria associations
Scenedesmus sp. [39]	Indole-3-acetic acid, 2,4- dichlorophenoxyacetic acid	Increase in growth, lipid and pigment accumulation
Phaeodatylum tricornutum [40]	Nitric oxide (NO)	Increased tolerance capacity of microalgae against stress factors
Chlamydomonas reinhardtii [41,42]	Rapamycin	Increase in cell growth due to the protein synthesis, accumulation of triacylglycerol and starch in the cell biomass
Chlorella vulgaris [24]	Perfluorohexane, perfluorodecalin	Increase in cell rate growth and biomass accumulation

It is interesting to note that the use of chemically modified phytohormone molecules for biotechnological regulation of the growth rate of commercially important microalgal cells has made it possible to reduce the concentration of added growth regulators by

an order of magnitude (tenfold), due to their more effective action compared to natural analogs [39].

It should be emphasized that not only phytohormones can be used by microalgae for intercellular communication and cooperation involving both prokaryotic and eukaryotic cells [37]. As signaling molecules, microalgae can also utilize bacterial QS molecules [27,36,37], as well as other inorganic and organic low-molecular-weight compounds [40–42]. These signaling agents are particularly important for diatom microalgae [40] and cyanobacteria, helping to increase their tolerance to various environmental stress conditions, as well as improving photosynthetic efficiency and growth rates.

It has been established that organic pollutants such as perfluorocarbons (PFCs), which possess the ability to perform gas-transport functions and carry oxygen, can stimulate the growth of microalgae and enhance their biomass accumulation [24]. This occurs because carbon dioxide, which serves as a substrate for microalgae, dissolves more effectively in PFCs than in pure water [43]. PFCs therefore improve the availability of carbon-containing gaseous substrates for microalgal cells and, under natural or biotechnological conditions where both types of microorganisms coexist, enhance the supply of oxygen (produced by phototrophs) to bacteria [44]. In turn, bacterial growth in media containing microalgae can further stimulate microalgal biomass accumulation due to the synthesis of bacterial QS signaling molecules (N-acyl-homoserine lactones, Table 1), which microalgal cells can utilize for similar regulatory purposes. Such dual activation through the presence of PFCs and the emergence of quorum molecules leads to a pronounced increase in the accumulation of mixed (bacterial–microalgal) biomass. This mechanism ensures the efficient activity of these cells in removing various pollutants (including pharmaceuticals [45], phenols and their derivatives [28], hydrocarbons [46], etc.) from wastewater.

Undoubtedly, understanding the effects of these specific regulators of microalgal cell accumulation is essential for addressing current environmental challenges and for accelerating the growth and biomass accumulation of microalgae for specific commercial applications [47,48].

3. Immobilized Cells of Phototrophic Microorganisms

3.1. Immobilized Forms of Individual Microalgal Cultures and Their Biotechnological Features

The development of immobilized forms of microalgae naturally requires the preliminary accumulation of a sufficient amount of microalgal biomass for its incorporation into various matrices or into spontaneously formed biofilms that actively develop with the participation of polysaccharides accumulated as a result of photosynthesis. As the amount of phototrophic cell biomass per unit volume increases, the concentration of substances regulating their QS and metabolic rearrangements in the direction desired by researchers also typically increases [21,49,50]. This allows for the creation of immobilized samples of individual microalgal cells (Table 2 [51–100]) with predictable and stable characteristics and, in a number of cases, to achieve an enhanced rate of biomass accumulation [63,65,78,81,84]. The information presented in Table 2 is based on the references retrieved from such databases as Google Scholar and Scilit. The keywords used for the information selection were “microalgae”, “cyanobacteria”, “phototrophic microorganisms”, “immobilization”, and “co-immobilization”. The selected publications had a retrospective value of the last five years.

Table 2. Various immobilized forms of microalgae and other phototrophic microorganisms, which have contributed to the improvement of the process based on their use.

Phototrophic Microorganisms [Reference]	Immobilized Form of Microalgae	Biotechnological Process	Appeared Positive Characteristics of the Process
Chlamydomonas reinhardtii [51]	Inclusion in Sr-alginate gel	Production of the H_2	Enhanced level of H_2 accumulation
Chlorella sp. [52]	Entrapment in Ca-alginate-cellulose nanofiber hydrogel	Bioremediation of aquaculture wastewater	Enhanced nutrient removal efficiencies
Chlorella vulgaris [53]	Inclusion in konjac glucomannan aerogel	Remediation of oil pollution	Improved crude oil biodegradation
Chlorella vulgaris [54]	Entrapment in Ca-alginate beads	Biohydrogen production	Enhanced biohydrogen production
Chlorella sorokiniana [55]	Entrapment in poly (vinyl alcohol) (PVA) cryogels	Wastewater treatment	Enhanced nutrient removal efficiency
Chlorella vulgaris [56]	Encapsulation in Ca-alginate hydrogel beads	Wastewater treatment, biohydrogen production	Phenol degradation and biohydrogen production
Desmodesmus sp. [57]	Encapsulation in Ca-alginate beads	Acid mine drainage (AMD) wastewater bioremediation	Method for Fe (II) removal from AMD effluent
Auxenochlorella protothecoides [58]	Immobilization within sugarcane bagasse	Biosorption of carcinogenic metal ions	Enhanced biosorption of Ni (II)
Chlorella vulgaris [59]	Inclusion in Ca-alginate hydrogel	Wastewater treatment and biomass production	Enhanced nutrients removal and biomass accumulation
Synechocystis sp. [60]	Encapsulation in Ca-alginate beads	Bioremediation of shrimp wastewater	Reduction in phosphates and harmful bacteria
Chlorella vulgaris [61]	Biofilm formation on the analcime-bearing rock	Biodegradation of recalcitrant organic pollutants	Increased phenol removal
Desmodesmus sp. [62]	Entrapment in Ca-alginate beads	Bioremediation of raw domestic wastewater	Enhanced nitrogen, phosphorus, and 17β-estradiol removal efficiencies
Synechocystis sp. [63]	Encapsulation in Ca-alginate beads	Succinate production	Increased growth and succinate productivity
Spirulina platensis [64]	Inclusion in Ca-alginate beads	Removal of Pb (II) from aqueous solutions	Enhanced adsorption of Pb (II)
Chlorella vulgaris [65]	Encapsulation in Ba-alginate bubble beads	Novel type of immobilized beads	Enhanced growth of microalgae
Chlorella vulgaris [66]	Encapsulation in Ca-alginate micro-nano bubble beads	Remediation of groundwater	Improved microalgal biomass and antibiotics removal efficiency
Euglena deses, *Chlamydomonas reinhardtii*, *Trichormus variabilis*, *Scenedesmus obliquus* [67]	Encapsulation in Ca-alginate beads	Bio-desalination of real seawater samples	Reduced amount of Cl^- ions
Chlorella vulgaris [68]	Entrapment in PVA-Na-alginate beads	Carbamazepine removal	Increased carbamazepine removal rate

Table 2. *Cont.*

Phototrophic Microorganisms [Reference]	Immobilized Form of Microalgae	Biotechnological Process	Appeared Positive Characteristics of the Process
Chlorella vulgaris [69]	Entrapment in Ca-alginate beads	Municipal wastewater reverse osmosis concentrate treatment	Improved nutrient remediation and biomass production
Chlorella vulgaris [70]	Encapsulation in Ca-alginate micro-nano bubble beads	Removal of antibiotics from groundwater	Improved ofloxacin removal efficiency
Chlamydomonas reinhardtii [71]	Encapsulated within Ca-alginate beads	Production of H_2	Enhanced sustainability and H_2 production
Tetradesmus obliquus *Chlorella pyrenoidosa* [72]	Encapsulation in Ca-alginate beads	Cd^{2+}-containing wastewater treatment	Enhanced removal efficiency of Cd^{2+}
Haematococcus pluvialis [73]	Entrapment within Ca-alginate hydrogel membrane	Production of astaxanthin	Enhanced astaxanthin accumulation
Chlorella vulgaris, *Scenedesmus abundans*, *Selenastrum capricornutum*, *Coelastrum microporum* [74]	Entrapment in Ca-alginate beads	Wastewater treatment	Enhanced nutrient removal efficiency
Porphyridium cruentum [75]	Entrapment in Ca-alginate beads	Sulfated polysaccharides (SPs) production	Enhanced cell biomass and SPs production
Chlorella sorokiniana [76]	Immobilization on corn cob	Removal of chromium ions from aqueous solution	Improved removal of chromium ions
Arthtospira (*Spirulina*) *platensis* [77]	Encapsulation in Ca-alginate beads	Removal of azo dyes from wastewater	Improved adsorption capacity
Chlorella minutissima [78]	Encapsulation in Ca-alginate beads	Production of biomass and bioactive compounds	Enhanced biomass growth and proteins, carotenoids, fatty acids production
Tetraselmis sp. [79]	Encapsulation in Sr-alginate beads	Aquaculture wastewater treatment	Improvement of water quality by reduction in nitrogenous waste
Chlorella sacchrarophila [80]	Immobilization on agar	Wastewater treatment	Increased nutrient removal efficiency
Chlorella vulgaris *Chlorella* sp. [81]	Encapsulation in Ca-alginate beads	Textile wastewater treatment	Increased pollutant removal efficiency, lipid accumulation
Chlorella vulgaris, *Scenedesmus quadricaud* [82]	Entrapment in Ca-alginate beads	Wastewater effluent treatment	Improved nutrient removal
Chlorella sp. [83]	Encapsulation in Ca-alginate beads	Treatment of pollutant sites in Dhiba port	Reduced number of organic compounds, metals, and metalloids
Chlorella vulgaris [84]	Immobilization on mixed matrix	Treatment of palm oil mill effluent	Potential for lipid, fatty acid methyl ester, biodiesel production
* Different types of microalgae [85]	Encapsulation in Ca-alginate beads	Bioremediation of shrimp aquaculture wastewater	Enhanced nutrient removal efficiency
Desmodesmus sp., *Heterochlorella* sp. [86]	Entrapment in Ca-alginate beads	Acid mine drainage remediation	Increased Fe removal

Table 2. *Cont.*

Phototrophic Microorganisms [Reference]	Immobilized Form of Microalgae	Biotechnological Process	Appeared Positive Characteristics of the Process
Chlorella sorokiniana [87]	Immobilization on dual carriers (sponge, activated carbon)	Piggery wastewater treatment	Enhanced nutrient removal efficiency
Nannochloropsis sp. [88]	Encapsulation in Ca-alginate beads	Treatment of palm oil mill effluent	Enhanced biomass accumulation and chemical oxygen demand (COD) removal
Chlorella vulgaris [89]	Entrapment in Ca-alginate beads	Bioremediation of municipal wastewater	Enhanced nutrients removal and biomass accumulation
Chlorella sorokiniana [90]	Immobilization into polyvinyl alcohol-optical fibers gel beads	Mitigation of self-shading effect	Enhanced light penetration and nutrient removal efficiency
Chlorella vulgaris [91]	Entrapment in Ca-alginate/carboxymethyl cellulose	Biomass accumulation for extraction of lipids	Enhanced lipid accumulation
Chlorella vulgaris, *Chlamydomonas reinhardtii* [92]	Encapsulation in Ca-alginate beads	Bioremediation of wastewater	Enhanced nutrient removal efficiency
Chlorella sorokiniana [93]	Inclusion in biofilm alga-copolymer	Bioremediation of wastewater	Enhanced removal efficiency of Cu^{2+}, Cd^{2+}
Scenedesmus obliquus [94]	Encapsulation in Ca-alginate beads	Alginate recycling method	Enhanced nutrient removal, reduced operational cost
Tetradesmus obliquus [95]	Encapsulation in Ca-alginate beads	Bioremediation of swine manure-based wastewater	Enhanced nutrient removal efficiency
Lobosphaera sp. [96]	Immobilization on chitosan-based carriers	Bioremediation of wastewater	Enhanced nutrient removal efficiency
Chlorella vulgaris [97]	Entrapment in Ca-alginate beads	Space life support systems	Ease of recovery, and suitability for automated, closed-loop bioregenerative
Chlorella vulgaris [98]	Encapsulation in Ca-alginate beads	Wastewater treatment	Improved nutrient removal, control of membrane fouling
Chlorella vulgaris [99]	Entrapment in Ca-alginate beads	Wastewater treatment	Improved nutrient removal
Chlorella sorokiniana [100]	Immobilization into modified mussel shell powder	Bioremediation of eutrophic wastewater	Enhanced nutrient removal efficiency

Note: * Different types of microalgae: *Nannochloropsis oculate*, *Dunaliella salina*, *Tetraselmis suecica*, *Chlorella marina*, *Picochlorum maculatum*, *Coelastrum* sp., *Chlorococcum* sp., *Chlorella* sp., *Synechocystis* sp., *Phormidium* sp., *Nostoc* sp., *Phormidium tenue*, *Anabaena* sp., *Amphora coffeaeformis*, *Amphora subtropica*, *Nitzschia microcephala*, *Navicula* sp.

Among all microalgal cultures used for the development and investigation of immobilized forms, representatives of the *Chlorella* genus, particularly *Chlorella vulgaris* and *Chlorella sorokiniana*, have been the most widely used in recent research. Their dominance

stems from a combination of biological robustness, physiological versatility, and technical compatibility of their cells with various immobilization matrices. *Chlorella* cells in immobilized form demonstrate rapid accumulation of free biomass under variable environmental and wastewater conditions, high tolerance to mechanical entrapment, and exceptional capacity for nutrient and pollutant removal.

Across fifty reviewed studies (Table 2), immobilized *Chlorella* strains consistently showed substantial removal of nitrogen and phosphorus (often exceeding 90% within 12 h of treatment) from wastewater, along with effective biosorption of heavy metals and organic micropollutants. For example, immobilized *C. vulgaris* increased carbamazepine removal efficiency from 67% (for suspended cells) to 84% [68], while dual-carrier immobilized *C. sorokiniana* achieved more than 90% reduction in COD, total nitrogen (TN), and total phosphorus (TP) in piggery wastewater [87].

Several studies have also demonstrated valuable co-benefits: *C. vulgaris* grown in palm-oil mill effluent accumulated lipids that can be converted to fatty acid methyl esters suitable for biodiesel production [84], while *C. minutissima* cells embedded in calcium–alginate beads produced proteins, carotenoids, and fatty acids for biorefinery applications [78]. Improvements in immobilization design have further enhanced performance: buoyant barium–alginate beads increased growth and harvesting efficiency [65]; embedded optical fibers reduced self-shading and increased photosynthetic activity by more than 20%; and optimization of bead size (approximately 3.5 mm), balanced light penetration and nutrient diffusion to maximize pollutant removal efficiency [90].

These results collectively highlight *Chlorella* cells as benchmark candidates for immobilization studies, combining high pollutant-removal capacity, physiological resilience, and the potential for simultaneous biomass and metabolite production. The repeated success of *Chlorella* across multiple matrices (alginate, polyvinyl alcohol (PVA), cellulose, chitosan, konjac glucomannan, etc.) underscores the genus' suitability as a model organism for the development of scalable, multifunctional immobilized microalgal systems (Table 2).

Immobilization matrices that provide favorable conditions for mass transfer of substrates and metabolites, as well as for cell growth and release, play a critical role in determining the stability, efficiency, and reusability of microalgal systems. Among the reviewed studies, calcium alginate remains the most widely used immobilization material due to its biocompatibility, mild gelation conditions, and ease of bead formation. The macroporous hydrogel network of this carrier provides sufficient mass-transfer conditions for nutrients and gases while maintaining cell entrapment and protecting inoculated cells from shear stress. However, several recent studies have explored composite and modified matrices that can overcome alginate's mechanical weaknesses and diffusion limitations. For instance, the incorporation of cellulose nanofibers into alginate hydrogels increased the rigidity of the beads and improved nitrogen and phosphorus removal by up to 15% from aquaculture wastewater [52].

Similarly, chitosan-based carriers exhibited enhanced phosphate and metal ions adsorption due to their polycationic functional groups [46], while PVA cryogels provided superior mechanical strength and reusability across multiple treatment cycles without loss of microalgal viability [68]. Moreover, it is noteworthy that PVA cryogels possess cryoprotective properties, allowing long-term storage of microalgal cells immobilized within this matrix [26].

Emerging hybrid supports, such as konjac glucomannan aerogels and sulfur-based copolymers, have introduced new functionalities, including hydrophobicity for oil adsorption and sulfur-mediated binding for nutrient biocapture [53,93].

The use of natural or waste-derived carriers (such as corn cob, mussel shell powder, lignocellulosic matrices, and analcime-bearing rock) has also attracted attention for enhanc-

ing sustainability and reducing material costs [58,61,76,100]. Optimization of bead size, alginate concentration, and Ca^{2+} cross-linking degree significantly influence diffusional rates and structural integrity. For instance, the alginate polymerization degree directly affects hydrogen yield and cell release kinetics during dark fermentation [54].

These developments clearly demonstrate a trend toward multifunctional immobilization systems in which mechanical reinforcement, sorptive capacity, and recyclability are integrated to improve both environmental performance and economic feasibility.

The primary field of application of immobilized microalgae remains wastewater treatment and valorization, with *Chlorella*-based systems leading across municipal, aquaculture, and industrial effluents. In aquaculture wastewater, immobilized *C. vulgaris* and *Tetraselmis* sp. provided nearly complete phosphate removal (>95%) and suppressed harmful bacterial growth, while alginate–cellulose composite beads maintained stable performance over multiple reuse cycles [52,79].

For high-strength industrial effluents such as palm-oil mill or textile wastewater, immobilized *C. sorokiniana* achieved more than 90% COD reduction and maintained active growth under high organic loads [81,84].

Several studies highlighted improved biosorption and detoxification capabilities: immobilized *Auxenochlorella protothecoides* on lignocellulosic matrices removed more than 95% of carcinogenic metal ions (Cd^{2+}, Cr^{6+}) [58], and *Spirulina platensis* alginate beads effectively adsorbed Pb(II) and azo dyes with 80–95% efficiency [64,77]. In addition, immobilized systems outperformed suspended cultures in terms of operational stability, ease of harvesting, and reusability, allowing for semi-continuous and multi-cycle treatments without significant activity loss [59,69,74,85]. Integration with micro-nano bubble technology and membrane bioreactors further enhanced oxygen transfer, reduced membrane fouling, and increased removal of antibiotics and pharmaceuticals by 20–40% [66,70,82].

Overall, these results indicate that immobilization enhances the feasibility of using microalgae for sustainable wastewater management by combining high pollutant-removal rates with the potential for valorization of biomass into biofuels, pigments, and other bioactive compounds.

3.2. Co-Immobilization of Microalgae with Other Microorganisms

Studies exploring the possibility of creating stable consortia of microalgae with other microorganisms to enhance pollutant biodegradation by increasing its depth, rate, and substrate diversity, have demonstrated the need to maintain highly concentrated populations of microalgal cells. Immobilization of microalgae in combination with other microbial "partners" is particularly suitable for these purposes. Such partners may include other phototrophic cells, mycelial fungi, but most often and most successfully bacteria (Table 3 [101–125]). It should be noted that co-immobilized "mixed population" systems display greater diversity of carriers and preparation methods compared with immobilized individual microalgal cultures (Table 2). The information presented in Table 3 is based on the references retrieved from such databases as Google scholar and Scilit. The keywords used for the information selection were "microalgae", "cyanobacteria", "phototrophic microorganisms", "immobilization", and "co-immobilization". The selected publications had a retrospective value of the last five years.

Table 3. Examples of co-immobilization of phototrophic microorganisms with other microbial cultures.

Phototrophic Microorganisms [Reference]	Microbial "Partner"	Carrier/Immobilization Method	Purpose of Use	Effect of Co-Immobilization
Bacteria co-immobilized with microalgae				
Chlorella vulgaris [101]	*Azospirillum brasilense*	Ca-alginate beads/ Gel inclusion	Increasing the lipid content in accumulating microalgae biomass	Increased activity of acetyl-CoA carboxylase and the level of accumulation of biomass with increased lipid content compared to immobilization of only microalgae cells
Chlorella vulgaris [102]	*Phyllobacterium myrsinacearum*	Ca-alginate beads/ Gel inclusion	Wastewater treatment	Increased synthesis of five pigments in microalgae cells
Scenedesmus obliquus [103]	*Paenibacillus polymyxa*	Chitosan coated K-carrageenan and Chitosan-coated Ca-alginate beads/Sorption	Increasing productivity of the target product	A 1.5-fold increase in the concentration of bacterial 2,3-butanediol and a 3-fold increase in the growth rate of microalgae
Tetradesmus obliquus [104]	*Alcaligenes faecalis*	Polyvinyl alcohol (PVA)- alginate-perylene diimide/ Gel inclusion	Tetracycline degradation	Significant reduction in the decomposition time of the antibiotic (1.25 days), increase in the efficiency of its decomposition (up to 94%)
Chlorella sp. [105]	*Bacillus subtilis*	Guar gum-K-carrageenan hydrogel/Sorption	Biofilter for the treatment of industrial effluent from vegetable oil factories	Increased efficiency of removal of wastewater components (NH^{4+}, PO_4^{3-}, COD—up to 53.5%, 68.6 and 98.7%, respectively) compared to microalgae cells alone
Chlorella vulgaris [106]	*Azospirillum brasilense*	Ca-alginate beads/Gel inclusion	Pig farm wastewater treatment	Increased removal efficiency of N-NH^{4+}, TN, P−PO_4^{3-} and TP up to 93.8%, 85.9%, 77.7% and 66%, respectively, compared to microalgae cells alone

Table 3. *Cont.*

Phototrophic Microorganisms [Reference]	Microbial "Partner"	Carrier/Immobilization Method	Purpose of Use	Effect of Co-Immobilization
Synechococcus leopoliensis or Chlorella vulgaris [107]	*B. subtilis*	Filling of polyurethane sponge with activated carbon/Sorption	Artificial pharmaceutical wastewater treatment with lincomycin	Increasing the efficiency of the developed biosorbent
Auxenochlorella sp. [108]	*Acinetobacter calcoaceticus*	Polyurethane sponges/Sorption	Simultaneous removal of several micropollutants	Enhanced removal (NH^{4+} and TN by bacteria and PO_4^{3-} by microalgae) through biomass recycling and accumulation
Microalgal–bacterial cultures [109]	Microalgal–bacterial cultures	Hybrid hydrogel made of PVA, alginate, and activated carbon/ Gel inclusion	Removing N and COD	Increase in nitrification rate to 0.43 mg N/g Total suspended solid/h
Scenedesmus sp. [110]	*Azospirillum brasilense*	Ca-alginate beads/ Gel inclusion	Reducing the impact of high concentrations of CuO nanoparticles	Increased growth rate and biochemical composition of accumulating biomass
Chlorella vulgaris [111]	*Pseudomonas putida*	I-doped TiO_2 hydrogel/ Sorption	Removal of phthalate esters	Increased phthalate ester removal efficiency and reduced CO_2 emissions using microalgae
Thermosynechococcus sp. [112]	*Chloroflexus aggregan*	Formation of aggregates	Use in biotechnological processes	Strengthening interspecies interactions and accumulation of necessary biomass
Fistulifera sp. [113]	*Dinoroseobacter shibae*	Biofilm	Suppression of toxic blooming	Changes in the species composition of the phytoplankton community
Active sludge co-immobilized with microalgae				
Chlorella pyrenoidosa [114]	Activated sludge	Simplifying modified PVA-sulfate method/ Gel inclusion	Wastewater treatment	Increased efficiency of nitrate removal (up to 80%) and phosphates (up to 88%), possibility of repeated use of the immobilized form of microorganisms (4 working cycles)

Table 3. *Cont.*

Phototrophic Microorganisms [Reference]	Microbial "Partner"	Carrier/Immobilization Method	Purpose of Use	Effect of Co-Immobilization
Chlorella vulgaris [115]	Activated sludge	Ca-alginate beads/ Gel inclusion	Synthetic wastewater treatment	Increased total nitrogen removal efficiency (up to 50%)
Filamentous fungi co-immobilized with microalgae				
Chlorella vulgaris [116]	PVA cryogel-entrapped Rhizopus oryzae, Aspergillus terreus	Sorption on fungal mycelium	Production of mixed biomass	Increased microalgae sorption
Haematococcus pluvialis [117]	*Aspergillus awamori*	Sorption on fungal mycelium	Production of biomass with specified properties	Increased microalgae sorption
Phaeodactylum tricornutum [118]	*Aspergillus* sp.	Sorption on fungal mycelium	Production of biomass with specified properties	Increased microalgae sorption
Synechocystis sp. [119]	*Aspergillus allahabdii*	Sorption on fungal mycelium	Adsorption of Cd(II)	Increase in sorption capacity for Cd(II) by 22.2% compared to cyanobacteria alone
Anabaena torulosa [120]	*Trichoderma viride*	Sorption on biofilm	Formulation of a preparation for stimulating agricultural plants	Changes in the metabolite profile (increased proportion of sugars, decreased concentration of amino acids)
Anabaena torulosa [121]	*Trichoderma viride*	Bt-cotton hybrid (Ajeet 155 BG II®)/Biofilm formation	Production of biofertilizer	Increase in cotton yield by 57–71%
Consortia of microalgae				
Scenedesmus obliquus [122]	*Chlamydomonas reinhardtii*	Ca-alginate beads/ Gel inclusion	Degradation of diclofenac	Change in the ratio between bioaccumulation and biodegradation of diclofenac towards its degradation
Scenedesmus sp. [123]	*Chlorella* sp.	Moving Bed Biofilm Reactors	Pig farm wastewater treatment with lincomycin	Increased efficiency of simultaneous removal of lincomycin (up to 99%) and ammonium (up to 94%), which are 30% and 15%, respectively, higher than without the co-immobilized culture variant

Table 3. *Cont.*

Phototrophic Microorganisms [Reference]	Microbial "Partner"	Carrier/Immobilization Method	Purpose of Use	Effect of Co-Immobilization
Scenedesmus sp. and *Chlorella* sp. [124]	*Aphanocapsa* sp.	Mixed biofilm	Purification of digestates and aquaculture waste	Increased carbon capture efficiency, removal of nitrogen and phosphorus compounds
Cylindrotheca closterium [125]	*Oscillatoria subbrevis*	Mixed biofilm	Mitigating the effects of shoreline erosion	Reduction in suspended solids concentration as a result of surface coating with biofilm

Bacterial and fungal QS molecules, which often share structural similarities, in particular the lactone nature of signaling molecules [126], regulate cross-kingdom interactions between these microorganisms and microalgal cells, as well as the metabolic activity of the phototrophs themselves [36,127]. This phenomenon is actively utilized in the development of highly efficient biocatalysts based on co-immobilized cultures [28]. In such systems, microalgae often serve as oxygen generators required by their aerobic partners, while simultaneously assimilating the carbon dioxide they produce [111,124]. Due to this symbiotic exchange, accelerated growth of microalgae cells is also observed in such systems, if growth-limiting or growth-inhibiting factors are absent [103,110,111]. Other phototrophic cells, diverse bacteria, mycelial fungi, and activated sludge, which usually represent a natural consortium with a complex microbial composition, are used as microbial partners in such co-immobilization systems (Table 3). In this context, the natural potential inherent in the cells themselves through their QS mechanisms and density-dependent regulation (Table 1) is realized. This potential imparts to the artificially created systems, by analogy with natural biofilms, high productivity of microalgae and resistance to unfavorable factors and stress conditions that may arise during their prolonged use in various biotechnological processes (Table 3).

Co-immobilization of cyanobacteria and bacteria through aggregate formation strengthens interspecies interactions [112]. Directed biofilm formation based on diatom microalgae and phototrophic bacteria allowed modification of species ratios and effective mitigation of toxic algal blooms [113]. An analysis of publications in recent years shows that mixed immobilized systems based on microalgae are primarily created using bacterial cells [101–113].

Interestingly, modern trends in the development of co-immobilized samples composed of phototrophic microorganisms and bacteria clearly indicate a shift away from calcium alginate [101,102], which previously was the most widely used carrier for pure microalgal cultures immobilization (Table 2), toward more complex, multicomponent materials [103–113]. This shift is driven by the growing need for multifunctional systems. Researchers increasingly strive to create composite materials where the carrier serves not merely as a structural matrix but also performs additional functions. For example, in co-immobilized microbial systems designed for the treatment of wastewater containing pharmaceutical pollutants, the carrier matrix itself often acts as a sorbent of xenobiotics, concentrating them for subsequent biodegradation [107].

When creating co-immobilized samples of microalgal and bacterial cells, the widest variety of carriers has been used compared to other co-immobilization variants (Table 3).

Co-immobilization of bacteria and microalgae (mainly of the *Chlorella* and *Scenedesmus* genera) is generally applied for wastewater treatment, targeting both organic and inorganic contaminants [104–106,108,109,111]. When co-immobilization is performed with activated sludge, *Chlorella* species are the preferred phototrophs (Table 3). Such cell combinations contribute to an increased degree of nitrogen compound removal from wastewater and convincingly demonstrate their operational efficiency [114,115].

The creation of immobilized systems based on phototrophs and mycelial fungi is achieved primarily through the sorption of microalgae and cyanobacteria on fungal hyphae, including immobilized ones (Table 3). This biosorption-based approach allows phototrophic biomass to accumulate on the surface of fungal mycelium, which requires good aeration, thereby enabling successful coexistence of both organisms. At the same time, such co-immobilized systems used in biotechnological processes can subsequently serve as mixed biomass samples with properties desirable for further conversion into various commercially valuable products [116–118]. Biofilms, particularly those with natural polymer substrates, formed using cyanobacteria *Anabaena torulosa* and the mycelial fungus *Trichoderma viride* [121], have been applied as highly effective biofertilizers.

There are mainly two current tasks in obtaining co-immobilized forms of phototrophic microorganisms with bacterial cells: changing the biochemical composition of the accumulated biomass or improving the characteristics of the wastewater treatment process (for example, in the case of co-immobilization of activated sludge with phototrophic microorganisms). The co-immobilized forms of mycelial fungi and phototrophic microorganisms are based on a nature-like process of phototrophic adhesion to the surface of fungal hyphae. The purpose of creating such systems is typically to facilitate the collection of biomasses of phototrophic microorganisms. Only recently have new prospects emerged for the use of such mixed types of microbial biomass in the form of biofertilizers that significantly improve plant growth [120,121].

Co-immobilized microbial samples obtained using several different phototrophic microorganisms have proven highly efficient in promoting the degradation of waste containing pharmaceutical pollutants, including veterinary drugs present in animal waste [122–124]. A particularly interesting and novel concept was the use of mixed phototrophic biofilms to address the problem of shoreline erosion [125]. This approach proved quite successful, and a reduction in erosion was experimentally confirmed.

Thus, co-immobilization of various microorganisms with microalgae is an actively developing field. Recent advances in applied science reveal several new trends, including [116,128]:

- the search for new combinations of participants in co-immobilized systems,
- the application of new carrier materials, predominantly of composite nature and often with improved sorptive characteristics,
- and the exploration of new directions for using these biological combinations, including their potential as resource bases enriched with accumulated microalgal biomass for subsequent conversion into commercially valuable products.

By analyzing the variety of data, we were able to establish the following conclusion: immobilization does not limit the growth of microalgae, it helps maintain phototrophic cells in a state of maximum proximity to each other in high concentrations, which contributes to the formation of highly concentrated populations that exhibit signs of cell functioning in a quorum state.

4. Analysis of the Current Trends and Perspectives in the Application of Immobilized Phototrophic Microorganisms

An analysis of recent studies related to the accumulation and use of microalgal biomass (Tables 2 and 3) demonstrates a clear and significant increase in new research results, as well as an obvious shift in scientific and practical interest towards the development of immobilized forms of these microorganisms, allowing for better control of their properties. Acceleration of biomass accumulation processes for both immobilization purposes and biotechnological applications requiring rapid cell growth is achieved by utilizing accumulated knowledge about QS in various microorganisms, including microalgae, and about molecules capable of participating in similar regulatory mechanisms (Table 1).

Comparing the objectives of immobilized microalgae systems described in studies published between 2023 and 2025 (as listed in Tables 2 and 3), it can be concluded that mixed systems of microorganisms are generally more suitable for the production of renewable biomass than pure cultures of microalgae or cyanobacteria (Figure 1). Co-immobilization and, consequently, co-cultivation of phototrophs with other microorganisms allows for a more diverse and efficient process of microalgal biomass generation. In addition, this approach offers a convenient method of "harvesting" the biomass through sorption onto larger partner cells (such as mycelial fungi) or via the formation of joint biofilms with bacteria (Table 3).

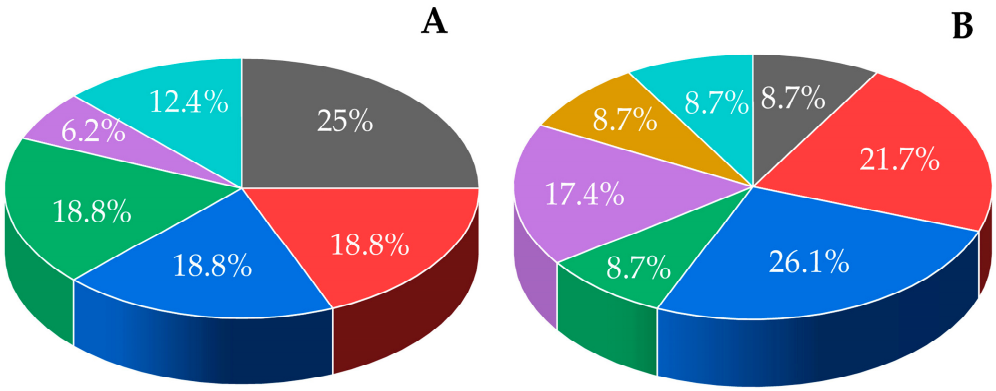


Figure 1. Intended applications of immobilized systems based on (**A**) only phototrophic cultures (n = 23) and (**B**) co-immobilized cells (n = 16), according to publications from 2023 to 2025 cited in this review (Tables 2 and 3): ■—production of commercially valuable products; ■—degradation of xenobiotics; ■—wastewater purification from organic compounds; ■—sorption and removal of metals; ■—accumulation of renewable biomass; ■—production of biofertilizers; ■—ecologically oriented processes. 100% corresponds to the total number of articles cited in this review containing the discussed information. The Origin Pro 2021 (ver. 9.8, OriginLab) software was used for data analysis and drawing. The retrospective period of the selected publications is three years.

Both types of immobilized systems are discussed: those based on individual microalgal cultures and those co-immobilized with other microorganisms are proposed by researchers for applications of ecological significance: seawater desalination, prevention of harmful algal blooms, and mitigation of shoreline erosion (Figure 1).

At the same time, immobilized pure phototrophic cultures are commonly recommended for the sorption and removal of metal particles. For wastewater treatment, mixed variants of immobilized microorganisms with microalgae are preferred, as such combinations are more effective. This effectiveness arises from the fact that bacterial cells, mycelial fungi, and microbial consortia intensify the transformation of pollutants, while phototrophs, in turn, stimulate their partners through oxygen synthesis and utilization of the carbon dioxide produced by them. Furthermore, microalgae use residual concentrations of simple

substances in the medium, as well as metabolites of their microbial partners, as nutrient sources. The combination of phototrophs with mycelial fungi of the genus *Trichoderma* allows for the accumulation of biomass, which can serve as a promising biofertilizer. Notably, no similar development trends were observed for pure microalgal biomass obtained from immobilized inoculates (Figure 1).

In the creation of immobilized preparations based on pure phototrophic cultures, researchers over the past three years (2023–2025) have predominantly used green microalgae, in particular species of the genus *Chlorella* (Figure 2). The share of cyanobacteria in such studies and developments has been relatively small, likely due to the toxins produced by these phototrophs [129]. It should be noted that there is growing evidence that in mixed microbial populations, bacteria play an important and effective role in detoxifying cyanobacterial toxins [130].

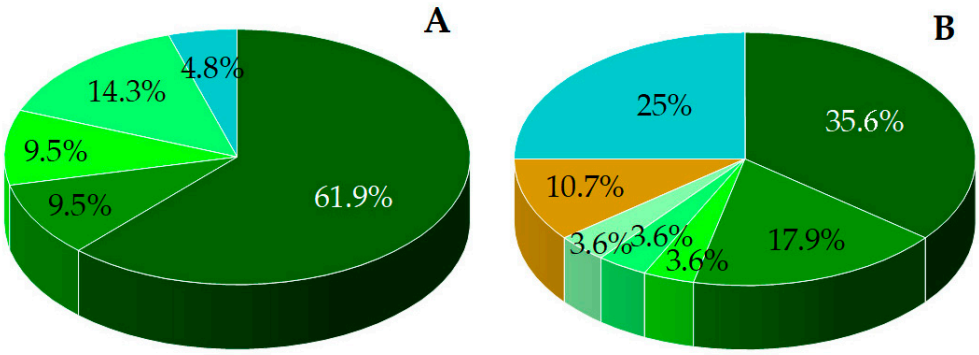


Figure 2. Distribution of phototrophic microorganisms used in the development of immobilized systems based on (**A**) only phototrophic cultures (n = 23) and (**B**) co-immobilized microorganisms (n = 16), according to publications from 2023 to 2025 cited in this review (Tables 2 and 3): ■—green microalgae (■—*Chlorella*; ■—*Scenedesmus;* ■—*Chlamydomonas*; ■—*Tetradesmus;* ■—*Haematococcus*); ■—diatom microalgae; ■—cyanobacteria. 100% corresponds to the total number of articles cited in this review containing the discussed information. The Origin Pro 2021 (ver. 9.8, OriginLab) software was used for data analysis and drawing. The retrospective period of the selected publications is three years.

An analysis of publications containing information on the use of co-immobilized phototrophs with other microorganisms was carried out, in comparison with the number of publications based on the use of an immobilized single culture of phototrophic microbial cells (Figure 3). Interest in immobilized single cultures has been found to be actually stable, with a slight but constant increase in recent years. At the same time, there has been a significant increase (per 40%) in interest in co-immobilized cells for accumulating the cells of phototrophic microorganisms as a source of phototrophic biomass. Furthermore, Figure 3 illustrates the preferential growth of investigations using co-immobilized phototrophic cells compared to immobilized single cultures. This is certainly a new trend in research development, revealed by an analysis of recent publications.

The conducted analysis also showed that the transition from immobilized pure microalgal cultures to co-immobilized variants significantly increases the proportion of studies involving not only cyanobacteria but also diatom microalgae. Interestingly, the inclusion of new phototrophic participants in co-immobilized systems with other microorganisms is often associated with the development of biosystems designed for novel or unconventional, yet highly creative, applications of the resulting biomass samples (Table 3).

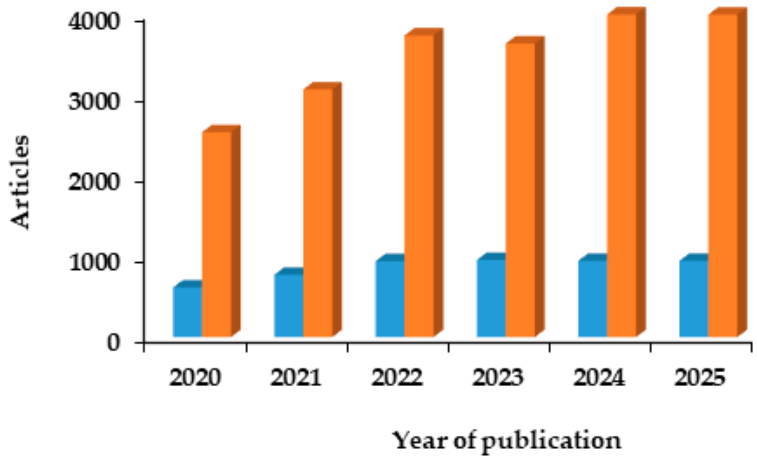


Figure 3. Chronological change in the number of scientific papers published and cited in the Google Scholar database, where ■ corresponds to the number of articles published with the search keyword "immobilized microalgae", ■ corresponds to the number of articles published with the search keyword "co-cultivation of immobilized microalgae." The Origin Pro 2021 (ver. 9.8, OriginLab) software was used for data analysis and drawing. The retrospective period of the selected publications is 2020-november 2025.

Summarizing the accumulated information regarding the prospects for further use of immobilized forms of phototrophic microorganisms, it can be stated that, due to the growing interest in the development of various composite materials, increased attention can be expected to the biotechnological production of phototrophic polysaccharides [28,131]. Their biotechnological synthesis is directly dependent on the ability to accumulate significant concentrations of microalgal producer cells capable of generating the desired polymers. From a practical perspective, further application of the accumulated knowledge on the controlled accumulation of biomass by immobilized phototrophic microorganisms, their biosynthesis of polysaccharides, and subsequent extraction, purification, and use of these polymers is of great interest.

It is evident that during the biosynthesis of such natural composite materials, various metals and their oxides can be incorporated into their structure [132], since immobilized and QS-active microalgal cells exhibit increased resistance to the medium components that might otherwise inhibit their growth or metabolic activity. As a result, such "green-metal-containing composites" could be promising for use in various fields requiring pathogen control due to their potential biopesticidal properties, including agriculture [132,133], as well as the production of construction materials (paints, grout, wallpaper adhesives, etc.) [134] and packaging materials [128].

An interesting result was obtained in a study involving co-immobilization of *Chlorella vulgaris* and *Phyllobacterium myrsinacearum* [102], where an increase in the synthesis of five different pigments by microalgal cells was observed. This work may be regarded as an indication of an alternative method for enhancing the synthesis of natural pigments which play an important role in many industries such as food, pharmaceuticals, and cosmetics, compared to approaches based on synthetic biology using CRISPR technology [135].

The observed prevalence of green microalgae, particularly species of the genus *Chlorella*, in various immobilized configurations of phototrophic microorganisms can be explained by the well-studied properties of these cells. Their biomass is attractive for use in numerous biotechnological processes and environmental applications, including the degradation and neutralization of microplastics [136], as well as acting as a soil quality improver (due to the formation of essential aggregates) and as a biofertilizer [121].

5. Conclusions

Currently, immobilized microalgal cells are used for several key purposes: to accumulate free cell biomass, to synthesize specific metabolites, and to remove unwanted or toxic substances from the environment (such as nitrogen-containing compounds, heavy metals, and various pollutants from wastewater). The application of immobilized microalgal cells in aquatic environmental studies can be significantly expanded in the near future. This is primarily due to the ongoing development of new materials and new combinations of cells involved in immobilization. Furthermore, the wider use of living microalgal cells as recognition elements in biosensors is expected, particularly in systems immobilized in electronic devices designed to assess the toxicity of substances and wastewater. Recent biotechnological studies have demonstrated the clear advantages of using immobilized mixed cell systems (biofilms containing both bacteria and microalgae) in wastewater treatment plants. Another promising area of applied science for the coming years is the use of microalgal biomass, rapidly grown using immobilized concentrated inoculate, for the production of environmentally friendly energy sources, such as hydrogen (H_2).

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Abbreviations

The following abbreviations are used in this manuscript:

AMD	Acid mine drainage
COD	Chemical oxygen demand
QS	Quorum Sensing
PFCs	Perfluorocarbons
SPs	Sulfated polysaccharides
TN	Total nitrogen
TP	Total phosphorus

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