Chapter 194

Biotechnological advances in the production of fungal chitosan

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ABSTRACT

Fungal biology has made important advances in recent decades, enabling the extraction of molecules of biotechnological interest, such as chitin, one of the most versatile and abundant biopolymers in nature. Several studies suggest that fungal organisms cultivated on a large scale can be used as an alternative source for obtaining this polysaccharide. Thus, this review presents the most recent biotechnological advances in the production of chitin and its derived products, evaluating the potential use of fungal organisms as a commercial source of this raw material.

Keywords: Fungal chitin, Chitosan, Biotechnology, Mucorales.

1 INTRODUCTION

The biology of fungi has presented important advances in recent decades, enabling the extraction of molecules of biotechnological interest, such as chitin, one of the most versatile and abundant biopolymers in nature, after cellulose (SOUZA et al., 2011). In addition to being the main constituent of the exoskeleton of insects and crustaceans, chitin is also found in fungi, mollusks, and yeasts (CREMAR et al., 2018).

It is a linear copolymer formed by repetitive monomeric units of β-1,4 N-acetyl D-glucosamine. With the use of alkali solutions, chitin undergoes deacetylation reactions giving rise to its copolymer, chitosan, which can also be naturally found as a structural component in the cell wall of some fungi, such as those belonging to the order Mucorales (BERGER et al., 2018).

The applications of chitin and chitosan have been growing rapidly due to their diverse properties such as biocompatibility, hemostatic activity, non-toxicity, adsorption, and anti-infectious properties, enabling their use in agricultural, environmental, medical, and pharmaceutical areas (GHORMADE; PATHAN; DESHPANDE, 2017). In addition, it is high biodegradability and production from renewable substrates further elevate its importance as a sustainable product, making it increasingly attractive to scientific and technological advances (BURANDE; DHAKITE; RAWAT, 2018).

Currently, the commercial production of chitin and its derived products occurs through the process of thermochemical deacetylation of chitin obtained from marine sources, such as shells of crustaceans (TOLESA; GUPTA; LEE, 2019). However, the supply of this source is seasonal and limited, resulting in

variability of the source material (ADNAN et al., 2017; BERGER et al., 2014). In addition, the physicochemical properties of chitin derivatives obtained from such processes are, for the most part, heterogeneous, and may present different molecular weights and degrees of deacetylation (KANNAN et al., 2010). Another concern of this process of obtaining is the use of strong alkaline solutions that constitute important sources of pollution for the environment (CAMPANA-FILHO et al., 2007) in addition to the presence of protein residues in the final product, which can cause allergic reactions in susceptible human beings (FRANCO et al., 2004).

In this sense, several studies suggest that fungal organisms grown on a large scale could be used as an alternative source for obtaining chitin. Thus, this review presents the latest biotechnological advances in the production of chitin and its derived products, evaluating the potential use of fungal organisms as a commercial source of these raw materials.

2 CHEMICAL AND MOLECULAR STRUCTURE OF CHITIN

Chitin is a natural polysaccharide, semicrystalline in a solid state and that performs a structural function in nature, constituting, for example, the exoskeleton of arthropods, conferring protection and mechanical resistance to these organisms (ZARGAR; ASGHARI; DASHTI, 2015). It is highly hydrophobic, being insoluble in water and most organic solvents (PILLAI; SWAMP; SHARMA, 2009), presents low chemical reactivity (LARANJEIRA; FÁVERE, 2009) and biodegradability (DUTTA; DUTTA; TRIPATHI, 2004).

As for its structure, chitin is presented as a linear polymer, whose repetitive unit is the disaccharide formed by 2-acetamide-2-deoxy-D-glucopyranose and 2-amino-2-deoxy-D-glucopyranose joined by glycosidic binding of type β (1→4), thus defining the reducing and non-reducing terminals of the polymer chains, which correspond to the ends containing free hydroxyl group of the glucopyranose ring (CAMPANA-FILHO et al., 2007).

The elucidation of the molecular structure of chitin and its chitosan copolymer took decades to complete. The molecular weight of these polysaccharides can reach 10^6 Da. The degree of N-acetylation and the degree of polymerization, which in turn decides the molecular weight of the polymer, are two important parameters that dictate the use of chitosan for various applications. Its influence on the development of the viscosity of aqueous solutions has significant roles in the biochemical and biopharmacological importance of chitin and chitosan. Typically, in chitin acetylation,>70% is expected, while by definition chitosan has a degree of acetylation <30–40%. There is no separate pathway for chitosan synthesis. Chitosan formation is commonly achieved in any organism by deacetylation of chitin using chitin deacetylase (GHORMADE et al., 2010).

Quitin is also known for exhibiting polymorphism, where it can be found in different forms of arrangements (α, β, and γ-chitin) being in its solid state, according to the arrangement of its polymeric chains in the leaves or lamellae that constitute the crystalline domain (ARANAZ et al., 2009). In α-chitin,

which is the most abundant in nature, the polymer chains are arranged in an antiparallel way, which favors the existence of numerous inter- and intra-chain hydrogen bonds of the same lamella and neighboring lamellae, resulting in a dense packaging (BATTISTI; CAMPANA-FILHO, 2008). In β-chitin the chains are arranged in a parallel arrangement, making it difficult to establish intermolecular and interlamellar hydrogen bonds, which results in less dense packaging (JANG et al., 2004). In γ-chitin, there seems to be a combination of the arrangements α and β, where every two lamellae are in a parallel arrangement, and a third lamella are arranged antiparallel (ARANAZ et al., 2009).

3 OCCURRENCES OF CHITIN AND CHITOSAN

It is estimated that the annual production of chitin and chitosan is almost as much as cellulose, becoming of great interest as a functional biomaterial, presenting a high potential for applicability in several fields(ZARGAR; ASGHARI; DASHTI, 2015). One of the main factors guiding the demand for chitosan is the easy availability of its raw material, chitin, whose main source comes from the residual product of the fishing industry.

In addition to being present in the carapace of crustaceans, chitin is also found in the matrix of the skeletal structure of invertebrates of various phyla, such as annelids, other types of arthropods, mollusks, and coelenterates, in diatomaceous algae, and in the cell wall of some fungi, especially in the species belonging to the order Mucorales (Table 1) (BERGER et al., 2018).

Table 1. Sources of obtaining chitin and chitosan

Classification	Phylum	Family	Example species	Reference
Marine organisms	Annelida	*Siboglinidae*	*Oligobrachia ivanovi*	(BLACKWELL et al., 1965)
	Mollusca	*Facelinidae*	*Pilgrim Cratena*	(MARTIN et al., 2007)
	Cnidaria	*Schizopathidae*	*Parantipathes larix*	(BO et al., 2012)
	Arthropoda	*Penaeidae*	*Litopenaeus vannamei*	(SANTOS et al., 2019)
	Arthropoda	*Potamidae*	*Potamon potamios*	(BOLAT et al., 2010)
	Arthropoda	*Palinuridae*	Polinurus vulgaris	(ACOSTA et al., 1993)
	Arthropoda	*Euphausiidae*	*Euphausia superba*	(WANG et al., 2013)
	Brachiopoda	*Lingulidae*	*Anatina Lingula*	(WILLIAMS et al., 1994)
Arachnids	Arthropoda	*Buthidae*	*Mesobuthus gibbosus*	(KAYA et al., 2016)
	Arthropoda	*Lycosidae*	*Geolycosa vultuosa*	(KAYA et al., 2014)
Insects	Arthropoda	*Formicidae*	*Camponotus floridanus*	(WANG et al., 2012)
	Arthropoda	*Scarabaeidae*	*Scarab beetles*	(BADAWY; MOHAMED, 2015)

	Arthropoda	*Blattidae*	*American per planet*	(BADAWY; MOHAMED, 2015)
Microorganisms	Mucoromycota	*Cunninghamellaceae*	*Cunningamella elegans*	(FRANCO et al., 2005)
	Ascomycota	*Saccharomycetaceae*	*Saccharomyces cerevisiae*	(BULIK et al., 2003)
	Microsporidia	*Unikaryonidae*	*Encephalitozoon cuniculi*	(PEUVEL-FANGET et al., 2006)
	Bacillariophyta	*Thalassiosiraceae*	*Thalassiosira fluviatilis*	(MCLACHLAN et al., 1965)
	Ascomycota	*Trichocomaceae*	*Penicillium chrysogenum*	(TIANWEI et al., 2002)
	Blastocladiales	*Blastocladiaceae*	*Allomyces arbuscula*	(MITCHELL; DEACON, 1986)

Source: Prepared by the author (2023).

4 SYNTHESES OF FUNGAL CHITIN

Fungal chitin has been discussed and studied in the world since 1859, having achieved important advances over the years. In Brazil, the first studies presenting techniques for the identification and quantification of biopolymers of microbiological origin were published by Campos-Takaki in mid-1978 (CAMPOS-TAKAKI, 1978) and early 80s (CAMPOS-TAKAKI, 1984). Currently, studies with chitin and fungal chitosan in Brazil and the world seek applications in the medical and pharmaceutical areas, given its antibacterial and antifungal properties against pathogenic microorganisms and ability to inhibit the proliferation of cancer cells (DENG et al., 2014).

Chitin can be found in the formation of mycelium of different fungal species, such as *Cunninghamella elegans* (SILVA et al., 2022a), Mucor *circinelloides* (FAI et al., 2011), *Mucor rouxii* (ABASIAN et al., 2020), *Absidia coerulea, Gongronella butleri* (NWE et al., 2011), *Aspergillus niger and Rhizopus arrhizus* (VIEIRA et al., 2020) have been considered as possible sources of chitin and chitosan due to their abundance in cell walls. Every chitin found in the inner wall of the fungal cell as a microfibril serves to compensate for the turgor pressure of the cells (DHILLON et al., 2013; HUQ et al., 2022).

The synthesis of chitin in fungi is highly compartmentalized. The key enzyme chitin synthetase occurs in the form of zymogen where it is distributed to specific regions on the cell surface in specialized vesicles called schistosomes. Macromolecular assembly begins outside the cytoplasm where the protease (activator) on the cell surface activates the zymogen. Once energy-rich uridine diphosphate-N-acetylglucosamine is produced (from glucose), chitin synthetase successfully catalyzes the transfer of GlcNAc to chitin-forming primers (THARANATHAN; KITTUR, 2003). In most fungi, chitin is synthesized from the polarized growth sites of the cell wall. A period of isotropic growth begins in large cells with buds, where the material is deposited on the entire surface of the yolk. After nuclear splitting, a repolarization phase begins where the material is directed to the parent button neck to prepare for

cytokinesis. In hyphal or filamentous forms, cell extension is a continuous and indefinite apical process (HUQ et al., 2022).

4.1 MUCORALES

The order Mucorales comprises ubiquitous organisms, mainly saprotrophic (HOFFMANN et al., 2013), also known as sugar fungi, given their enzymatic ability to catabolize glucose and/or sucrose by rapidly consuming the entire substrate of the medium. They are economically important as fermenting agents of soybean products and producers of enzymes, but also as parasites of plants and deteriorating organisms (HOFFMANN et al., 2013; WALTHER et al., 2013). As one of the largest orders in basal fungi, Mucorales is also one of the most studied groups in physiological and biochemical aspects, as well as its taxonomy and potential applications in different industries (SPATAFORA et al., 2016).

The fungal species belonging to the order Mucorales are the ones that present the greatest potential for chitosan extraction, when compared to other fungi (BERGER et al., 2018) since they naturally present chitin and chitosan as a structural component of their cell wall, which an important physiological and taxonomic characteristic of the species (STAMFORD et al., 2007).

The deacetylation process of chitin occurs naturally in Mucorales with the participation of the enzymes chitin deacetylase and chitin synthetase (YUTANI et al., 2011). Chitin deacetylase is involved in the nutrition, morphogenesis, and development of fungi (GHORMADE et al., 2010), participating in the formation and integrity of the cell wall (BAKER et al., 2007), in germline adhesion (GEOGHEGAN; GURR, 2016), in the formation of spores, in fungal autolysis (WHITE et al., 2002) and the defense mechanisms during host infection (SÁNCHEZ-VALLET; MESTERS; THOMMA, 2015). Studies indicate that the activity of chitin deacetylase and its function in the biosynthesis of chitosan in the cell wall of the fungus indicates that enzymatic deacetylation has much milder conditions and that it overcomes most of the disadvantages found in the alkaline deacetylation process, aiming at increasing the microbiological production of this polymer (PAREEK; SINGH; GHOSH, 2011).

5 MICROBIOLOGICAL PRODUCTION OF CHITIN AND CHITOSAN

The production of quitina from the mycelial biomass of fungi has become the target of several studies that indicate that the content of polysaccharides present in the cell wall may suffer variations according to the fungal species, fermentation techniques, and nutritional conditions of the medium, especially concerning the carbon sources used in the production process (AKILA, 2014; CAMPOS-TAKAKI, 2005), as shown in Table 2.

The growth of several species of fungi, especially those representing the order Mucorales, is evaluated in several studies that seek to achieve greater biomass production and, consequently, higher yields of chitin and microbiological chitosan. For this, different synthetic culture media and low-cost alternative media have been tested. Among the alternative means are the residues of industries, and products or agro-

industrial residues such as jacatupé (FAI et al., 2011), maize, and manipueira (SILVA et al., 2022b), aiming at the possibility of large-scale production.

Table 2. Production of biomass, chitin and chitosan by Mucorales cultivated in different media reported in the literature.

Microorganisms	Substrate	Biomass ($^{g.L-1}$)	Chitin (mg. $^{g-1}$)	Chitosan (mg. $^{g-1}$)	Reference
R. arrhizus	Corn and manipueira	8,80	54,38	20,51	(BERGER, 2013)
R. arrhizus	Corn and juice of papaya peel	3,75	137,14	77,76	(BERGER, 2013)
R. arrhizus	Molasses and corn	24,6	83,2	49,31	(BERGER et al., 2014)
R. arrhizus	Corn and bee honey	20,6	-	29,3	(CARDOSO et al., 2012)
R. arrhizus	Corn 4%	13,00	30,40	12,85	(LINS et al., 2010)
R. arrhizus	Mamycin and glycerin	22,5	-	44,46	(SILVA, 2015)
R. arrhizus	Corn 8%	16,8	575	416	(SILVA, 2007)
R. microsporus	Molasses, malt pomace and tomato	12,6	485,71	150	(ARAÚJO, 2018)
R. oryzae	Corn and manipueira	1,24	-	44,67	(LIMA et al. , 2011)
R. oryzae	Corn straw	14,6	-	8,57	(OMOGBAI; IKENEBOMEH, 2013)
R. oryzae	Corn and manipueira	8,0	-	115,6	(LIMA et al. , 2011)
A. coerulea	Soybean bagasse	21,38	-	5,88	(JIANG et al. , 2011)
A. corymbifera	Mamycin and glycerin	21	-	88	(SILVA et al. , 2010)
M. circinelloides	Jicama	20,70	500	64	(FAI et al., 2011)
M. nightingale	Soybean meal and husk	-	-	34,4	(MONDALA et al., 2015)
C. elegans	Jicama	24,30	440	66	(STAMFORD et al., 2007)
C. elegans	Corn and manipueira	6,375	-	101,7	(SILVA et al., 2022a)
C. elegans	Corn and manipueira	5,67	89,39	57,82	(BERGER et al., 2014)
C. elegans	Corn and juice of papaya peel	4,11	126,0	77,78	(BERGER, 2013)
C. elegans	Maize and papaya husk	-	-	37,25	(BERGER et al., 2018)
C. elegans	Medium YPD	25,0	-	20,5	(AMORIM et al., 2001)
C. elegans	Andrade *et al.*	11,6	238	78,0	(SOUZA et al., 2011)
C. echinulata	Corn 1% and green banana flour 5%	1,1643	-	154,2	(PEREIRA- GOMES et al. , 2013)
C. bertholletiae	Cane juice	7,70	-	128	(AMORIM et al., 2006)
G. bulteri	Apple pomace	0,091	-	178,3	(STREIT et al., 2009)
A. niger	Broth Potato Dextrose	9.00	-	107	(POCHANAVANICH; SUNTORNSUK, 2002)
Z. nightingale	Yeast malt extract broth	4,4	-	36	(POCHANAVANICH; SUNTORNSUK, 2002)
C. albicans	Yeast malt extract broth	1,8	-	44	(POCHANAVANICH; SUNTORNSUK, 2002)
M. racemosus	Medium YPD	15,0	-	35,1	(AMORIM et al., 2001)
S. racemosum	Maize and tangerine husk	25	-	30	(MILK, 2014)

S. racemosum	Avocado peel	17	-	16,4	(MILK, 2014)
S. racemosum	Banana peel	8	-	25	(MILK, 2014)
S. racemosum	Sugarcane and maize bagasse	32	-	23,5	(MILK, 2014)

Source: Prepared by the author (2023).

Thus, the use of mycelial biomass has proven to be a good alternative since it is an easy and economically viable process, and simultaneous extraction of chitin and chitosan can be performed (BERGER et al., 2018). Another advantage is in the extraction methods since the cultivation of the fungus is independent of seasonality and also reduces the environmental impact generated by the residual products resulting from the deacetylation of the α-chitin, in which the varied purification processes of the biopolymer extracted from crustaceans produce large amounts of chemical pollutants (GHORMADE; PATHAN; DESHPANDE, 2017).

6 CONCLUSION

Chitin has attracted everyone's attention, given its versatility of application, being of great interest to the industry and scientific community. With the advances of fungal biotechnology, numerous advantages have been offered in the simultaneous production of fungal chitin over classical processes, since this biomaterial can be produced with simple and economical extraction processes, since many fungal species have great potential in the bioconversion of alternative substrates, such as agro-industrial waste. It is anticipated that its additional specific applications will be realized shortly.

REFERENCES

Abasian, l. Et al. Sustainable and effective chitosan production by dimorphic fungus mucor rouxii via replacing yeast extract with fungal extract. Applied biochemistry and biotechnology, v. 191, p. 666–678, 2020.

Acosta, n. Et al. Extraction and characterization of chitin from crustaceans. Biomass and bioenergy, v. 5, n. 2, p. 145–153, 1993.

Adnan, o. Et al. A novel biocoagulant agent from mushroom chitosan as water and wastewater therapy. Environmental science and pollution research, v. 24, n. 24, p. 20104–20112, 2017.

Akila, r. M. Fermentative production of fungal chitosan, a versatile biopolymer (perspectives and its applications). Advances in applied science research, v. 5, n. 4, p. 157–170, 2014.

Amorim, r. V. D. S. Et al. Alternative carbon sources from sugar cane process for submerged cultivation of cunninghamella bertholletiae to produce chitosan. Food technology & biotechnology, v. 44, n. 4, 2006.

Amorim, r. V. Da s. Et al. Faster chitosan production by mucoralean strains in submerged culture. Brazilian journal of microbiology, v. 32, n. 1, p. 20–23, 2001.

Aranaz, i. Et al. Functional characterization of chitin and chitosan. Current chemical biology, v. 3, n. 2, p. 203–230, 2009.

Araújo, j. F. De. Produção de quitosana e bioemulsificante por rhizopus microsporus (ucp 1304) através da fermentação submersa utilizando resíduos agroindustriais. Dissertação—recife: universidade católica de pernambuco, 2018.

Badawy, r. M.; mohamed, h. I. Chitin extraction, the composition of different six insect species and their comparable characteristics with that of the shrimp. Journal of american science, v. 11, n. 6, 2015.

Baker, l. G. Et al. Chitosan, the deacetylated form of chitin, is necessary for cell wall integrity in cryptococcus neoformans. Eukaryotic cell, v. 6, n. 5, p. 855–867, maio 2007.

Battisti, m. V.; campana-filho, s. P. Obtenção e caracterização de α-quitina e quitosanas de cascas de macrobrachium rosembergii. Química nova, v. 31, n. 8, p. 2014–2019, 2008.

Berger, l. Et al. Green conversion of agroindustrial wastes into chitin and chitosan by rhizopus arrhizus and cunninghamella elegans strains. International journal of molecular sciences, v. 15, n. 5, p. 9082–9102, 2014.

Berger, l. R. R. Produção e caracterização de quitina e quitosana por rhizopus arrhizus e cunninghamella elegans e aplicação em membranas na remoção de cádmio. Recife: universidade federal de pernambuco, 2013.

Berger, l. R. R. Et al. Chitosan produced from mucorales fungi using agroindustrial by-products and its efficacy to inhibit colletotrichum species. International journal of biological macromolecules, v. 108, p. 635–641. 2018.

Blackwell, j.; parker, k. D.; rudall, k. M. Chitin in pogonophore tubes. Journal of the marine biological association of the united kingdom, v. 45, n. 3, p. 659–661, 1965.

Bo, m. Et al. Isolation and identification of chitin in the black coral parantipathes larix (anthozoa: cnidaria). International journal of biological macromolecules, v. 51, n. 1–2, p. 129–137, 2012.

Bolat, y. Et al. Chitin-chitosan yield of freshwater crab (potamon potamios, olivier 1804) shell. Pakistan veterinary journal, v. 30, n. 4, p. 227–31, 2010.

Bulik, d. A. Et al. Chitin synthesis in saccharomyces cerevisiae in response to supplementation of growth medium with glucosamine and cell wall stress. Eukaryotic cell, v. 2, n. 5, p. 886–900, 2003.

Burande, b. C.; dhakite, p. A.; rawat, s. G. Studty of biopolymers based on renewable resources - a review. V. 4, n. 1, p. 5, 2018.

Campana-filho, s. P. Et al. Extracao, estruturas e propriedades de alpha-e beta-quitina. Química nova, v. 30, n. 3, p. 644, 2007.

Campos-takaki, g. M. De. Quitina em archlya radiosa (oomycetes: inibição por polioxina d, isolamento e caracterização). Dissertação—são paulo: universidade federal de são paulo (unifesp), 1978.

Campos-takaki, g. M. De. Aspectos bioquímicos e ultraestruturais das paredes celulares de fungos de ordem mucolares (zygomycetes). Tese de doutorado—são paulo: universidade federal de são paulo (unifesp), 1984.

Campos-takaki, g. M. The fungal versatility on the copolymers chitin and chitosan production. Chitin and chitosan opportunities and challenges, p. 69–94, 2005.

Cardoso, a. Et al. Microbial enhance of chitosan production by rhizopus arrhizus using agroindustrial substrates. Molecules, v. 17, n. 5, p. 4904–4914, 27 abr. 2012.

Cremar, l. Et al. Development of antimicrobial chitosan based nanofiber dressings for wound healing applications. Nanomedicine journal, v. 5, n. 1, p. 6–14, 1 jan. 2018.

Deng, x. Et al. Hyaluronic acid-chitosan nanoparticles for co-delivery of mir-34a and doxorubicin in therapy against triple negative breast cancer. Biomaterials, v. 35, n. 14, p. 4333–4344, 2014.

Dhillon, g. S. Et al. Green synthesis approach: extraction of chitosan from fungus mycelia. Critical reviews in biotechnology, v. 33, n. 4, p. 379–403, dez. 2013.
Dutta, p. K.; dutta, j.; tripathi, v. S. Chitin and chitosan: chemistry, properties and applications. 2004.

Fai, a. E. C. Et al. Physico-chemical characteristics and functional properties of chitin and chitosan produced by mucor circinelloides using yam bean as substrate. Molecules, v. 16, n. 8, p. 7143–7154, 2011.
Franco, l. De o. Et al. Heavy metal biosorption by chitin and chitosan isolated from cunninghamella elegans (ifm 46109). Brazilian journal of microbiology, v. 35, n. 3, p. 243–247, 2004.

Franco, l. De o. Et al. Cunningamella elegans (ifm 46109) como fonte de quitina e quitosana. Revista analytica, v. 4, n. 14, p. 40–44, 2005.

Geoghegan, i. A.; gurr, s. J. Chitosan mediates germling adhesion in magnaporthe oryzae and is required for surface sensing and germling morphogenesis. Plos pathogens, v. 12, n. 6, p. E1005703, 2016.

Ghormade, v. Et al. Chitin deacetylase: a comprehensive account on its role in nature and its biotechnological applications. 2. Ed. [s.l: s.n.].

Ghormade, v.; pathan, e. K.; deshpande, m. V. Can fungi compete with marine sources for chitosan production? International journal of biological macromolecules, v. 104, p. 1415–1421, nov. 2017.

Hoffmann, k. Et al. The family structure of the mucorales: a synoptic revision based on comprehensive multigene-genealogies. Persoonia - molecular phylogeny and evolution of fungi, v. 30, n. 1, p. 57–76, 30 jun. 2013.

Huq, t. Et al. Sources, production and commercial applications of fungal chitosan: a review. Journal of bioresources and bioproducts, v. 7, n. 2, p. 85–98, 1 maio 2022.

Jang, m.-k. Et al. Physicochemical characterization of α-chitin, β-chitin, and γ-chitin separated from natural resources. Journal of polymer science part a: polymer chemistry, v. 42, n. 14, p. 3423–3432, 2004.
Jiang, l.; pan, s.; kim, j. M. Influence of nitrogen source on chitosan production carried out by absidia coerulea ctcc af 93105. Carbohydrate polymers, v. 86, n. 1, p. 359–361, ago. 2011.

Kannan, m. Et al. Production and characterization of mushroom chitosan under solid-state fermentation conditions. V. 4, n. 1, p. 10, 1 ago. 2010.

Kaya, m. Et al. A physicochemical characterization of fully acetylated chitin structure isolated from two spider species: with new surface morphology. International journal of biological macromolecules, v. 65, p. 553–558, 2014.

Kaya, m.; asan-ozusaglam, m.; erdogan, s. Comparison of antimicrobial activities of newly obtained low molecular weight scorpion chitosan and medium molecular weight commercial chitosan. Journal of bioscience and bioengineering, v. 121, n. 6, p. 678–684, jun. 2016.

Laranjeira, m. C. M.; fávere, v. T. De. Chitosan: functional byopolymer with biomedical industrial potential. Química nova, v. 32, n. 3, p. 672–678, 2009.

Leite, m. V. Quitosana produzida por syncephalastrum racemosum ucp 1302 usando resíduos agroindustriais: caracterização e aplicação. Doctoralthesis. Disponível em: <https://repositorio.ufpe.br/handle/123456789/24327>. Acesso em: 4 abr. 2019.

Lima, j. M. De n.; campos-takaki, g. M.; okada, k. Produção do complexo quitosana - polifosfato em rhizopus oryzae ucp 1506 utilizando substratos agroindustrais. [s.l.] universidade católica de pernambuco, 2011.

Lins, c. I. M. Et al. Evaluation of chitin and chitosan by different extraction methods from mucoralean fungi biomass. Asian chitin j, v. 6, p. 5–8, 2010.

Martin, r. Et al. Granular chitin in the epidermis of nudibranch molluscs. The biological bulletin, v. 213, n. 3, p. 307–315, 2007.

Mclachlan, j.; mcinnes, a. G.; falk, m. Studies on the chitan (chitin: poly-n-acetylglucosamine) fibers of the diatom thalassiosira fluviatilis hustedt: i production and isolation of chitan fibers. Canadian journal of botany, v. 43, n. 6, p. 707–713, 1965.

Mitchell, r. T.; deacon, j. W. Selective accumulation of zoospores of chytridiomycetes and oomycetes on cellulose and chitin. Transactions of the british mycological society, v. 86, n. 2, p. 219–223, 1986.

Mondala, a. Et al. Direct solid-state fermentation of soybean processing residues for the production of fungal chitosan by mucor rouxii. Journal of materials science and chemical engineering, v. 03, n. 02, p. 11, 21 jan. 2015.

Nwe, n. Et al. Laboratory scale production of 13c labeled chitosan by fungi absidia coerulea and gongronella butleri grown in solid substrate and submerged fermentation. Carbohydrate polymers, v. 84, n. 2, p. 743–750, 1 mar. 2011.

Omogbai, b. A.; ikenebomeh, m. Solid-state fermentative production and bioactivity of fungal chitosan. Journal of microbiology, biotechnology and food sciences, p. 4, 2013.

Pareek, n.; singh, r. P.; ghosh, s. Optimization of medium composition for enhanced chitin deacetylase production by mutant penicillium oxalicum saem-51 using response surface methodology under submerged fermentation. Process biochemistry, v. 46, n. 8, p. 1693–1697, 2011.

Pereira- gomes, m. Das d.; campos-takaki, g. M. De. Influência dos resíduos agroindustriais (milhocina e farinha de banana verde) na produção de carboidratos totais, quitosana e lipídios por cunninghamella echinulata ucp 1297. [s.l.] universidade federal de pernambuco, 2013.

Peuvel-fanget, i. Et al. Enp1 and enp2, two proteins associated with the encephalitozoon cuniculi endospore, the chitin-rich inner layer of the microsporidian spore wall. International journal for parasitology, v. 36, n. 3, p. 309–318, 2006.

Pillai, c. K. S.; paul, w.; sharma, c. P. Chitin and chitosan polymers: chemistry, solubility and fiber formation. Progress in polymer science, v. 34, n. 7, p. 641–678, 2009.

Pochanavanich, p.; suntornsuk, w. Fungal chitosan production and its characterization. Letters in applied microbiology, v. 35, n. 1, p. 17–21, 2002.

Sánchez-vallet, a.; mesters, j. R.; thomma, b. P. H. J. The battle for chitin recognition in plant-microbe interactions. Fems microbiology reviews, v. 39, n. 2, p. 171–183, mar. 2015.

Santos, v. P. Et al. Recovery of chitin and chitosan from shrimp waste with microwave technique and versatile application. Arquivos do instituto biológico, v. 86, 2019.

Silva, á. F. S. Et al. Green synthesis of chitosan by cunninghamella elegans ucp 1306 using sustainable substrates mediated morphological changes. Research, society and development, v. 11, n. 7, p. E38211729387–e38211729387, 2022a.

Silva, á. F. S. Et al. Produção fúngica de quitina e quitosana utilizando resíduos agroindustriais como fontes sustentáveis de carbono e nitrogênio. Brazilian journal of development, v. 8, n. 1, p. 3562–3573, 2022b.

Silva, a. C. Da. Produção de quitina e quitosana em cultura submersa de rhizopus arrhizus nos meios milhocina e sintético para mucolares. Recife: universidade católica de pernambuco, 2007.

Silva, a. M. Da. Processo de produção e otimização de biomassa e quitosana por rhizopus arrhizus e aplicação biotecnológica. Recife: universidade federal de pernambuco, 2015.

Silva, a. M. Da; campos-takaki, g. M.; albuquerque, c. D. C. De. Produção de quitosana por absidia corymbifera em meio de baixo custo e aplicação na descoloração de efluente industrial. [s.l.] universidade católica de pernambuco, 2010.

Souza, c. P. Et al. The importance of chitin in the marine environment. Marine biotechnology, v. 13, n. 5, p. 823, 2011.

Spatafora, j. W. Et al. A phylum-level phylogenetic classification of zygomycete fungi based on genome-scale data. Mycologia, v. 108, n. 5, p. 1028–1046, set. 2016.

Stamford, t. C. M. Et al. Growth of cunninghamella elegans ucp 542 and production of chitin and chitosan using yam bean medium. Electronic journal of biotechnology, v. 10, n. 1, p. 61–68, jan. 2007.
Streit, f. Et al. Production of fungal chitosan in liquid cultivation using apple pomace as substrate. Brazilian journal of microbiology, v. 40, n. 1, p. 20–25, 2009.

Tharanathan, r. N.; kittur, f. S. Chitin—the undisputed biomolecule of great potential. 2003.
Tianwei, t.; binwu, w.; xinyuan, s. Separation of chitosan from penicillium chrysogenum mycelium and its applications. Journal of bioactive and compatible polymers, v. 17, n. 3, p. 173–182, 2002.

Tolesa, l. D.; gupta, b. S.; lee, m.-j. Chitin and chitosan production from shrimp shells using ammonium-based ionic liquids. International journal of biological macromolecules, v. 130, p. 818–826, 2019.

Vieira, e. R. Et al. *Rhizopus arrhizus* ucp1295 como fonte econômica para produção de biopolímeros funcionais quitina e quitosana utilizando substratos renováveis. Brazilian journal of development, v. 6, n. 10, p. 76444–76456, 2020.

Walther, g. Et al. Dna barcoding in mucorales: an inventory of biodiversity. Persoonia - molecular phylogeny and evolution of fungi, v. 30, n. 1, p. 11–47, 30 jun. 2013.

Wang, y. Et al. Chitin synthase 1 gene and its two alternative splicing variants from two sap-sucking insects, nilaparvata lugens and laodelphax striatellus (hemiptera: delphacidae). Insect biochemistry and molecular biology, v. 42, n. 9, p. 637–646, set. 2012.

Wang, y. Et al. Crystalline structure and thermal property characterization of chitin from antarctic krill (euphausia superba). Carbohydrate polymers, v. 92, n. 1, p. 90–97, 2013.

White, s. Et al. The autolysis of industrial filamentous fungi. Critical reviews in biotechnology, v. 22, n. 1, p. 1–14, 2002.

Williams, a.; cusack, m.; mackay, s. Collagenous chitinophosphatic shell of the brachiopod *lingula*. Philosophical transactions of the royal society of london. Series b: biological sciences, v. 346, n. 1316, p. 223–266. 1994.

Yutani, m. Et al. Morphological changes of the filamentous fungus mucor mucedo and inhibition of chitin synthase activity induced by anethole. Phytotherapy research, v. 25, n. 11, p. 1707–1713, 2011.

Zargar, v.; asghari, m.; dashti, a. A review on chitin and chitosan polymers: structure, chemistry, solubility, derivatives, and applications. Chembioeng reviews, v. 2, n. 3, p. 204–226, jun. 2015.