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SCOPING REVIEW ON ALTERNATIVE RENEWABLE MATERIALS TO IMPROVE SEED QUALITY

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ABSTRACT

The purpose of this review was to analyze and synthesize the published research on renewable alternative materials for improving seed quality to reduce pollution and raw material depletion. The analysis focused on productivity by country and authors, as well as the most relevant keywords. The articles were selected from the SCOPUS® and Web of Science™ databases, with updates until November 2021. Subsequently, they were analyzed by bibliometric indicators using VOS viewer v.1.6.15 and BIBLIOMETRIX v.3.0 software. The results show a global low in scientific production, with a total of 61 publications; the highest number of publications appears in 2020, with thirteen scientific reports. The most cited and prolific authors were Abbas HK, Accinelli C, and Shier WT. The United States of America was the country with the most publications (14). The most recently used keywords were "chitosan", "biopolymer", "seed coating", "maize (*Zea mays* L.)", "seed treatment", and "sustainable agriculture". The most widely documented developments were biostimulants, biocontrol, containers, and protective drought agents. Interdisciplinary collaboration could promote the discovery of new materials derived from renewable sources that have a significant impact on seed quality.

Keywords: treatment, protection, coating, dressing, bibliometric analysis.

INTRODUCTION

To withstand adverse conditions such as fungi and insect attack, seeds are usually protected with insecticides, fungicides, coating films, and other polymers, which also contribute to modifying their physical characteristics, including permeability, size, and shape. Because of the depletion of raw materials and pollution generated by some agrochemicals and materials, several authors and companies have proposed renewable alternative materials to improve seed quality, such as chitin and chitosan to improve germination and growth (Rahman *et al.,* 2018), vermicompost and soy flour to stimulate growth and development (Amirkhani *et al*., 2019), bioplastics for seed

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coating to reduce dusting (Accinelli *et al*., 2016; 2018b), *Aspergillus flavus* as a biocontrol of aflatoxin production (Accinelli *et al*., 2018a), chitosan and copper nanoparticles to boost defense responses (Choudhary *et al*., 2017; Divya *et al*., 2020); and bacteria-based biocomposites to stabilize the surrounding rhizosphere (Hussain *et al.,* 2019). Other materials have been proposed to enhance plant and plantlet development, such as recycled tomato waste and hemp fibers for biodegradable pots (Schettini *et al*., 2013).
The overall advance of studies on the use and development of renewable alternative materials for seed protection and germination promotion is unknown; a scoping review can update the extent of the topic and consists of gathering information followed by a bibliometric analysis (Verdejo *et al.,* 2021). The use of bibliometric indicators allows for objective and measurable quantitative data-driven evaluation (Flores-Fernández and Aguilera-Eguía, 2020), allowing to infer research trends over time and detect more prolific researchers and institutions, thus, presenting an "overview" of the subject (Aria and Curcurullo, 2017).
Bibliometric laws refer to those statistical expressions used to describe the functioning of science by mathematical means, among the most important of which is Lotka's law (Kumar, 2020). This type of review increases methodological rigor and helps develop well-founded knowledge by accumulating data of the existing literature, trends, and issues of current research (Verdejo *et al.,* 2021) through a reproducible design for identifying, evaluating, and interpreting the data by the PRISMA statement (Tricco *et al.,* 2018). The bibliometric analysis is a utility tool to measure and evaluate scientific research quantitatively and qualitatively (Sweileh, 2021) and to compare the connection among countries, authors, research volumes, and the activity of institutions for better allocation of funding.
The VOSviewer software is used in bibliometric analysis to estimate the association strength between two elements based on the separation distance, for which an optimization technique is used to form clusters from a set of tightly related nodes. The association strength (s_{ij}) between two terms, i and j, is calculated with the following (van Eck and Waltman, 2009):

$$s_{ij} = \frac{c_{ij}}{w_i w_j}$$

where c_{ij} denotes the number of co-occurrences of items i, j, w_i, and w_j denote either the total number of occurrences of items i and j, respectively, or the total number of co-occurrences of these items. Therefore, the term c_{ij} is the number of co-occurrences between articles i and j. Details on VOSviewer's mapping, normalization, and grouping methods are cited (van Eck and Waltman, 2009; Waltman *et al*., 2010).

The current study intends to analyze and synthesize the published research on renewable alternative materials to improve seed quality in order to reduce pollution and raw material depletion. This research focuses on describing the principal characteristics of relevant documents, as well as the connections between countries, authors, and emerging themes.

To fulfill the objective, we established a set of research questions (RQ):

(RQ1) How has research in the area of study progressed in terms of scientific publications and citations? (RQ2) What materials derived from renewable sources have been developed for seed improvement? (RQ3) Who are the researchers with the most scientific publications? What effect did their citation have? (RQ4) Which country has the most outstanding production of scientific articles related to the subject of study?

MATERIALS AND METHODS

Scoping review

The next five phases followed the proposed by Arksey and O'Malley (2005): defining research question or questions; identifying all the relevant studies; selection of the relevant studies; shaping the data; gathering, summarizing, and reporting the results. Two inclusion criteria were considered as follows: only documents such as "research articles" were considered, with no limitations on publication year or language; only papers focused on the development of alternative materials for improving germination, growth, crop yield, and physical and phytosanitary protection of seeds and seedlings were included.

The bibliographic search was made using the SCOPUS® and Web of Science ™ databases, these databases are the most complete digital source of scientific articles with peer-review journals with rigorous selection criteria for publishers and the most used in the bibliometric analysis (Sweileh, 2021). First, general concepts were used to search for articles related to alternative materials for seeds; later, more specific concepts were used to guide the search within the agricultural area using the logical Boolean operators "AND" & "OR" (Maçaira *et al.*, 2018).

Bibliometric analysis

The analysis was conducted with the R-tool for BIBLIOMETRIX 3.0 software BIBLIOSHINY (Aria and Curcurullo, 2017) and VOSviewer version 1.6.14 (van Eck and Waltman, 2009). BIBLIOSHNY was used to calculate Lotka's law and the H index after obtaining annual and authors' scientific output over time in terms of the number of publications. Lotka´s law is an approximate inverse-square law in which the number of authors publishing a certain number of articles is a fixed ratio to the number of authors publishing a single paper (Elango and Rajendran, 2012). The H index measures the broad impact of an individual's work while avoiding the drawbacks of other criteria. It provides an objective measurement of an author's academic works' impact and relevance (Hirsch, 2005). Bibliometric indicators of co-authorship and co-occurrence with countries and all keywords as the unit of analysis.

In VOSviewer, equal weight was given to co-authorship and citation of a publication ("fractional counting") regardless of the number of authors, citations, or references (Perianes-Rodriguez *et al.*, 2016).

RESULTS AND DISCUSSION

The initial keyword search yielded 4558 references (Figure 1). In the end, 61 articles remained in the matrix, comprising all the documents for the bibliometric analysis.

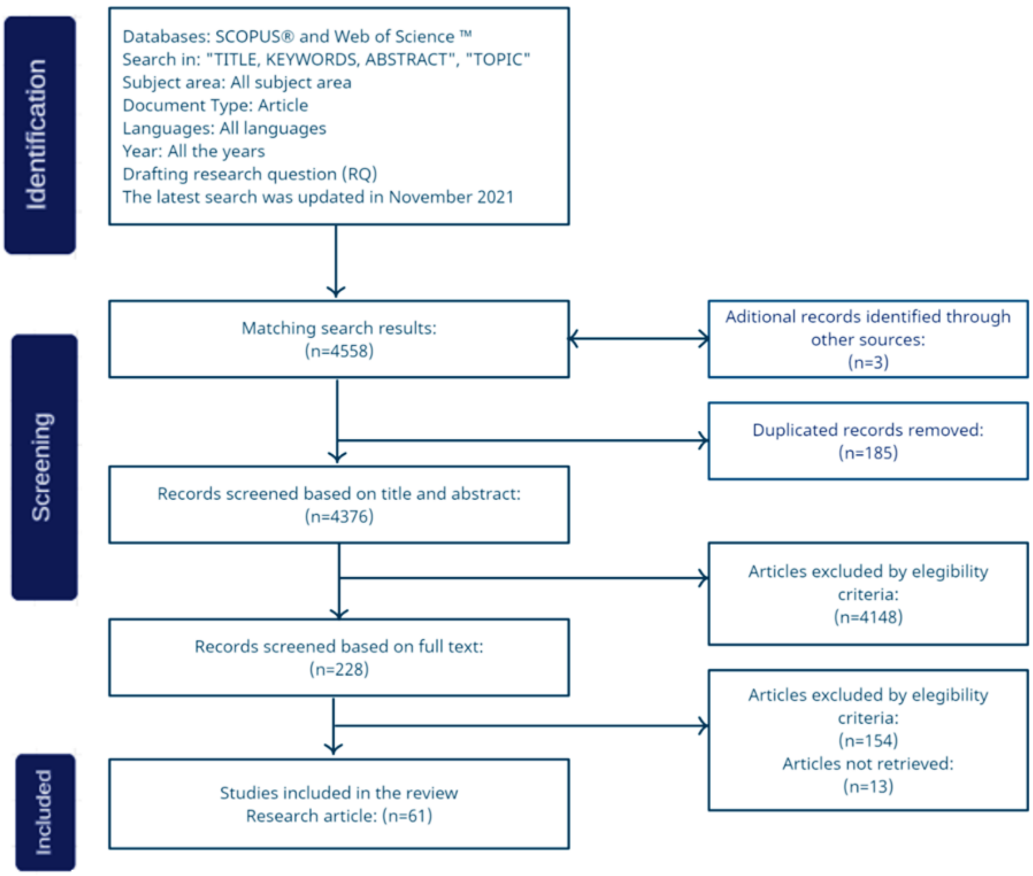

Figure 1. Stages of scoping literature review (modified from Tricco *et al.*, 2018)

Descriptive bibliometric analysis

There were 61 articles published between 2007 and 2021 (Table 1). The most influential journals were Crop Protection, Journal of Crop Improvement, PLOS One, and Scientific Reports with two documents, followed by Sustainable Chemistry and Engineering, Acta Agrobotanica, Acta Horticulturae, and African Journal of Biotechnology (with one document each). On average, every article has been cited 15 (14.66) times, and was written by five authors (4.92). The collaboration index (CI) was 5.12.

Table 1. Main information of articles on renewable alternative materials for seed protection.

Description of result	Results
Years of publication	2007–2021
Occurrence of journals	57
Number of documents	61
Years between each publication (average)	4.59
Number of citations per article (average)	14.66
Yearly number of citations per document (average)	2.59
Total number of references	2607
Research articles	60
Erratum	1
Number of phrases that frequently appear in the title of an article´s references	754
Number of keywords	232
Number of authors	300
Articles with a single author	3
Multi-authored articles	297
Number of documents by author (average)	0.20
Number of authors by document (average)	4.92
Number of co-authors for each article	5.38
Collaboration Index	5.12

Scientific production

Citations for publications about seed and seedling protection materials have gradually increased over time (Figure 2). This may be related to recent concerns about environmental preservation and reducing food loss and waste.

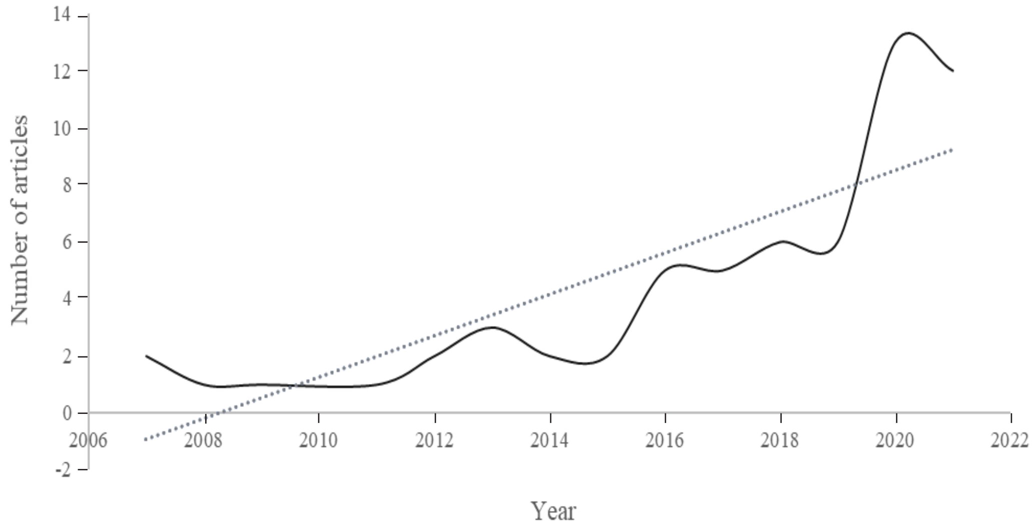

Figure 2. Papers published between 2007–2021 on renewable alternative materials for seed protection.

Renewable alternative materials and their applications

Bibliometric network co-occurrence resulted in a total of 183 words distributed into 14 clusters (Table 2). The keywords with the highest occurrence and total link strength which indicate the number of publications when two keywords occur together (Guo *et al*., 2019) were chitosan, biopolymer, seed coating, maize (*Zea mays* L.), seed treatment, sustainable agriculture, growth, and rice (*Oryza sativa* L.) (Figure 3). The most recently

Table 2. Co-occurrence network for unit keywords about renewable alternative materials for seed protection.

Cluster	Keyword	Occurrence	Total link strength	Average publication year
13	Chitosan	8	8	2018
	Antioxidant	2	2	2020
5	Biopolymer	5	5	2018
	Bioagent	2	2	2020
	Seed biopriming	1	1	2021
7	Seed coating	5	5	2017
	Sustainable Agriculture	3	3	2020
	Biomaterial in agriculture	1	1	2021
	Food security	1	1	2021
1	Maize (*Zea mays* L.)	4	4	2018
	Seed treatment	3	3	2017
6	Growth	3	3	2016
	Rice (*Oryza sativa* L.)	3	3	2013
8	Plant growth Promoting bacteria (pgpr)	3	3	2015
	Nitrogen-fixing bacteria (microorganisms)	2	2	2019
	Stomatal conductance of leave	1	1	2021
12	Ajowan (*Carum copticum* L.)	2	2	2016
	Salt stress	2	2	2020
3	Biological control	2	2	2009
	Rhizoctonia solani J.G. Kühn 1858	2	2	2015
10	Plant growth regulator	2	2	2019
	Salinity	2	2	2015
2	Biochar	2	2	2018
	Heavy metal	2	2	2018
	Nickel toxicity	1	1	2021
	Oxidative stress	1	1	2021
4	Chitin oligosaccharide	2	2	2019
	Electron beam plasma	2	2	2020
	Plant biostimulants	1	1	2021
11	Seed germination	2	2	2020
	Leaf production	1	1	2021
	Shoot elongation	1	1	2021
9	Carboxymethyl cellulose	2	2	2017

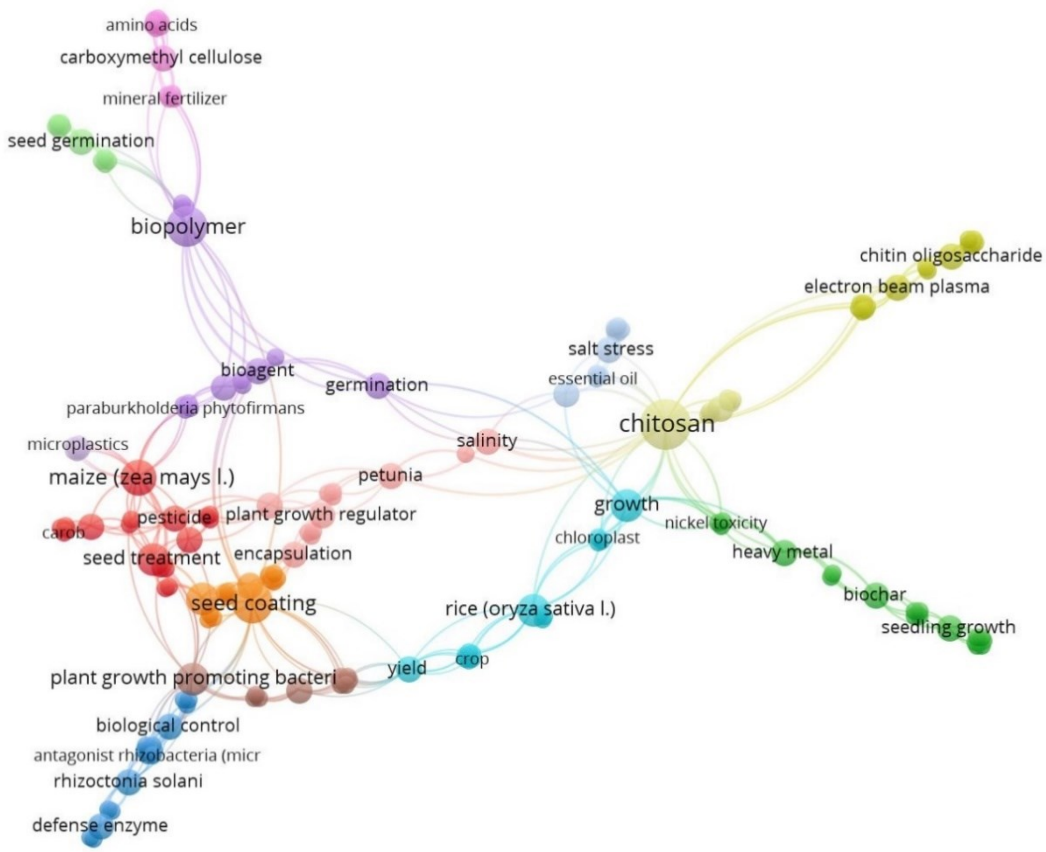

Figure 3. Clusters of keywords about renewable alternative materials for seed protection based on the strength and frequency of their association.

used keywords were those related to biomaterials in agriculture, food security, plant biostimulants, seed biopriming and care, including leaf production, shoot elongation, stomatal conductance of leaves, nickel toxicity, and oxidative stress (Figure 4).

The articles are listed from highest to lowest according to the number of citations (Table 3). Choudhary *et al.* (2017), with a research article on biostimulants and biocontrol, ranked first with 105 citations, approximately 17 per year, on the application of Cu-Chitosan nanoparticles (NPs) against *Curvularia lunata* (Wakker) Boedijn 1933 leaf spot disease on maize seeds. This review discussed the use of chitosan and chitin in various forms: chitosan oligosaccharide (COS) in biocontrol against *Tobacco mosaic virus* (TMV) (Jia *et al*., 2016) and chitosan nanoparticles (ChNP) against the sheath blight pathogen (ShB) (Divya *et al.,* 2020). Chitin, as a plant growth promoter in *Arabidopsis thaliana* (L.) Heynh. seeds, increased fresh weight (10 %) and radicle length (25 %) (Winkler *et al.,* 2017). Oligomeric chitosan increased leaf and root fresh and dry weight on the seeds and seedlings of rice (Chamnanmanoontham *et al.,* 2014) and ajowan (*Carum copticum* (L.) Benth. & Hook. f. ex C.B. Clarke). Under salt stress, chitosan promoted

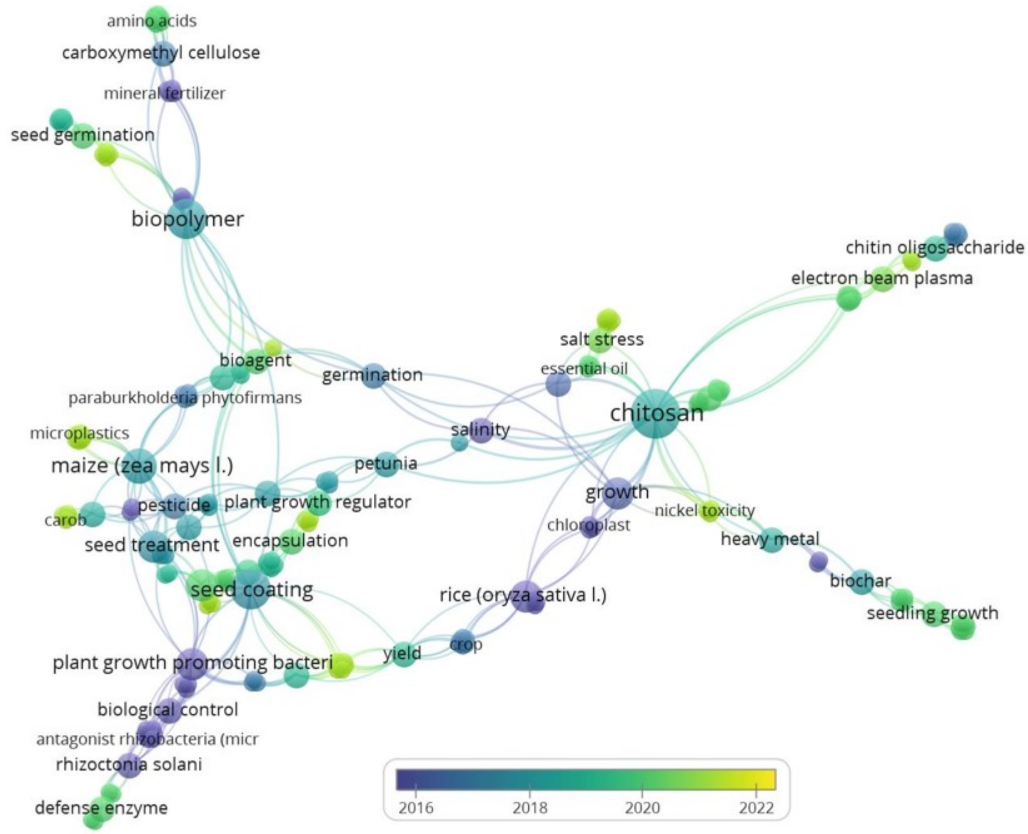

Figure 4. Bibliometric network showing the time-lapse for the appearance of keywords about renewable alternative materials for seed protection.

germination percentage and rate, seedling vigor index, length, dry weight, and radicle formation (Mahdavi and Rahimi, 2013). The application of foliar chitosan to strawberry seedlings increased growth and fruit production, as well as the concentration of total antioxidants, flavonoids, phenolics, carotenoids, and anthocyanins (Rahman *et al*., 2018). These agents were used in crops because of their importance to food safety and high added value.

Other developments presented (Table 3) include containers made of natural fibers from hemp hulls and strands used for bell pepper seeds, which produced very dense and active root hairs (Schettini *et al.,* 2013). A seedling tray made with polylactic acid (PLA) for rice seedlings caused an increase in the emergence rate and an average root diameter 8.63 % greater than the control (Shi *et al*., 2017). Containers made for *Posidonia oceanica* (L.) Delile "egagropili" fibers provided growth-supporting protection and anchoring to the plants (Balestri *et al*., 2019). These biocontainers improve environmental sustainability by reducing seed and seedling losses.

Table 3. Applications of renewable alternative materials used for seed protection.

Total of Citations	Citations per Year	Application	Material	Reference
105	17.5	Biocontrol and biostimulant	Cu-chitosan NPs + chitosan + CuSO4 + commercial fungicide (Bavistin)	Choudhary *et al*., 2017
68	9.7	Biocontrol agent	Chitosan oligosaccharide	Jia *et al*., 2016
49	4.9	Biodegradable pots improving agronomic crop yield	Sodium alginate + natural fibers from hemp hulls and strands	Schettini *et al*., 2013
48	8	Biostimulant	Chitin	Winkler *et al*., 2017
44	2.7	Biocontrol agent for *Aspergillus niger*	*Paenibacillus polymyxa* (Prazmowski 1880) Ash *et al*. 1994	Haggag, 2007
41	8.2	Biostimulant	Chitosan	Rahman *et al*., 2018
41	5.1	Plant growth promoter	Oligomeric and polymeric chitosan	Chamnanmanoontham *et al*., 2014
36	5.1	Offsetting phytotoxicity for metal nanoparticles	Extracellular polymeric substances (EPS)	Li *et al*., 2016
35	5	Biostimulant for germination	Biochar I (mixed wood sievings from wood chip production), Biochar II (mixture of paper sludge and wheat husks) and Biochar III (sewage sludge)	Gascó *et al*., 2016
34	3.4	Seed priming to improve germination, growth, and alleviate abiotic stresses	Acetic acid + chitosan	Mahdavi and Rahimi, 2013
31	5.2	Improving agronomic crop yield	Diazotrophic bacterial (*Azospirillum brasilense* strain Ab-V5) + biopolymer matrix	Oliveira *et al*., 2017
30	2.8	Nematicidal activity	Chitosan	Khalil and Badawy, 2012
27	3.9	Seed coating	*Trichoderma harzianum* Rifai 1969, anamorphic, strain T-22 (ATCC 20847) + insecticide (imidacloprid) + fungicide (metalaxyl-M+Starch)	Accinelli *et al*., 2016
21	7	Improving germination and plant growth in the presence or absence of a fungal pathogen (*Fusarium oxysporum* Schltdl. 1824)	Cellulose acetate + gelatin from porcine skin + acetic acid (695092, ACS reagent), Tween® 80 + copper (II) oxide nanopowder + copper acetate monohydrate	Xu *et al*., 2020
20	6.7	Stimulating effect on seedling growth	Biochar from rice straw (RS) and wood sawdust (WS)	Zhang *et al*., 2019
19	6.3	Antifungal for aflatoxin B1 (AFB1)	Chitosan + sodium-tripolyphosphate + dichloromethane (DCM) + glacial acetic acid (GAA) + dimethyl sulfoxide (DMSO) + methylglyoxal (MG) + perchloric acid + Tween-20 + Tween-80 + silica gel + ethanol + methanol + 2,2-diphenyl-1-picrylhydrazyl (DPPH) + 2,2′-Azino-bis (3 ethylbenzothiazoline-6-sulfonic acid) + diammonium salt (ABTS)+ PDA and SMKY	Kumar *et al*., 2020

Table 3. Continue.

Total of Citations	Citations per Year	Application	Material	Reference
18	1.5	Biocontrol and biofertilizer agent	*Bacillus subtilis* microcapsule	Hernández-Suárez *et al.*, 2011
18	6	Seed priming for growth stimulation and pest biocontrol	Chitosan	Jogaiah *et al.*, 2020
17	5.7	Biostimulant	*Trichoderma harzianum* Rifai 1969, strain T22 + biopolymer (carboxymethyl cellulose and Pluronic)	Carillo *et al.*, 2020
17	3.4	Biocontrol by seed coating	Starch with pesticides (insecticide: imidacloprid; fungicide: metalaxyl-M) and spores of non-aflatoxigenic *Aspergillus flavus* NRRL 30797 + chitin + glycerol	Accinelli *et al.*, 2018b
16	1	Chitosan for drought and plant yield recovery	Acetic acid + chitosan	Boonlertnirun *et al.*, 2007
14	2.8	Biocontrol and biostimulant by seed coating	Modified corn starch + chitin + glycerol + insecticide + fungicide	Accinelli *et al.*, 2018a
12	3	Seed coating biostimulants, biopesticides, and biofertilizer for yield improvement and seedling strengthening	Poly(vinyl alcohol) (PVA) and poly-(vinylpyrrolidone) (PVP) + glycerol + canola (*Brassica napus* L. cv. Faisal canola (RBN-03060)] + *Bacillus subtilis* NH-100 + fungal strains (*Macrophomina phaseolina* (Tassi) Goid. 1947, *Rhizoctonia solani* J.G. Kühn 1858, and *Fusarium oxysporum* Schltdl. 1824)	Hussain *et al.*, 2019
11	1.1	Encapsulated seeds	Sodium alginate + calcium chloride	Sakhanokho *et al.*, 2013
10	1.7	Biostimulant	Arabic gum + carboxymethylcellulose (CMC) + dextran + gelatin + glycerol + saponin + xanthan + alginate, egg lecithin, soy lecithin, skimmed milk + chitosan (food grade) + castor oil	Bejarano *et al.*, 2017
10	3.3	Biostimulant for improving plant tolerance to oxidative stress under salinity	NaCl + chitosan + acetic acid + Murashige and Skoog nutrient medium (MS)	Razavizadeh *et al.*, 2020
10	2.5	Seed coating biostimulant for seed germination and growth	Micronized vermicompost + defatted soybean meal + vegetable protein + diatomaceous earth (DE) + xanthan gum (XG)	Amirkhani *et al.*, 2019
8	1.1	Seed coating to improve native plant establishment	Biochar from ponderosa (*Pinus ponderosa* Douglas ex C. Lawson) and lodgepole (*Pinus contorta* Douglas ex Loudon) pine logs	Williams *et al.*, 2016
7	0.5	Seed priming to improve germination, biocontrol and management of pearl millet downy mildew disease	Gum biopolymers + metalaxyl (Apron 35 SD)+ methyl-N-(2-methoxyacetyl)-N-(2.6-xylyl)-DL-alaninat	Sudisha *et al.*, 2009

Table 3. Continue.

Total of Citations	Citations per Year	Application	Material	Reference
7	1.4	Growth stimulator	Chitosan	Krupa-Małkiewicz and Fornal, 2018
7	3.5	Seed germination promoter	Chitosan + alginic acid sodium salt + sodium tripolyphosphate (STPP) + copper(II) oxide nanopowder	Leonardi *et al.*, 2021
7	2.3	Biofungicide	Chitosan-hexaconazole-dazomet	Maluin *et al.*, 2020
6	1.5	Germination and biostimulant	Bio-oil derived from algae biomass *Macrocystis pyrifera* L.	Sankaranarayanan *et al.*, 2019
5	0.6	Biostimulator	Chitosan	Salachna *et al.*, 2015
5	0.8	Biodegradable seedling trays improving seedling quality	PLA (polylactic acid)	Shi *et al.*, 2017
4	1	Biocontainer for crops	*Posidonia oceanica* L. fibers + poly(3-hydroxybutyrate-co-3-hydroxyvalerate) + acetyl tributyl citrate + calcium carbonate	Balestri *et al.*, 2019
4	1.3	Stimulant for seed germination and biomass production	Chitosan + softwood lignocellulose	Vasilieva *et al.*, 2020
3	0.3	Reduce Fusarium mycotoxins	b-d-glucan biopolymers	El-Naggar and Thabit, 2014
3	1.5	Promoter seed germination	Chitooligosaccharide (COS)	Vasilieva *et al*., 2021
3	1	Biocontrol for ShB caused by *Rhizoctonia solani* J.G. Kühn 1858	Chitosan + acetic acid	Divya *et al*., 2020
2	0.2	Stimulating germination and plant growth	Xanthan gum + carboxymethyl cellulose sodium salt + fertilizers + micronutrients	Struminska *et al.*, 2014
2	0.2	Seed and seedling protection and growth stimulation	Chitosan + hemicelluloses (galactoglucomannans)	Niekraszkiewicz *et al*., 2012
2	1	Improving soybean tolerance to Ni toxicity	Chitosan	Sadeghipour, 2021
2	1	Seed biopriming	Sodium alginate + carboxymethylcellulose + gum arabic + xanthan gum + *Trichoderma asperellum* Samuels, Lieckf. & Nirenberg 1999	Chin *et al.*, 2021
2	1	Biocontrol	Biopolymer from the leguminous plant *Ceratonia siliqua L.* + *Trichoderma harzianum* Rifai 1969, M10 + *Trichoderma atroviride* Bissett 1984, P1 + *Trichoderma longibrachiatum* Rifai 1969, MK1	D'Errico *et al.*, 2020
2	0.7	Essential oil-based natural herbicides	Savory (*Satureja hortensis* L.) essential oil (EO) + natural polymers (i.e., arabic gum/gelatin (AGG), apple pectin (AP), gelatin (G))	Taban *et al*., 2020
2	0.7	Agent anti-drought	Chitosan oligosaccharide	He *et al.*, 2020

Table 3. Continue.

Total of Citations	Citations per Year	Application	Material	Reference
2	0.5	Biostimulant for germination and seedling growth, biopesticide	Chitosan	Zohara *et al.*, 2019
1	0.7	Seed germination and vigor	Chemical fungicide (CA) + biological fungicide polymers (chitosan-lignosulphonate polymer (CL) and eugenol incorporated into chitosan-lignosulphonate polymer (E+CL))	Thobunluepop *et al.*, 2008
1	0.2	Biocontainer	90 % polylactic acid (PLA) and 10 % lignin, 60 % PLA and 40 % soy polymer with adipic anhydride	Flax *et al.*, 2018
1	0.5	Stimulating effect for germination	Chitosan + alginate/PEG + commercial inoculant (HiStick® Soy)	Jarecki, 2021
1	0.5	Biocontrol for *Arabidopsis thaliana* (L.) Heynh. against salinity	Bentonite and l-proline	Merino *et al.*, 2021
1	0.5	Stimulating effect for germination and growth plant	Chitosan+ alginate with PGR (plant growth regulators)	Vlahoviček-Kahlina *et al.*, 2021
1	0.5	Minimizing abrasion losses	Sepiret (BASF, Ludwigshafen Germany) + starch-based liquid bioplastic + soy protein	Accinelli *et al*., 2020
1	0.3	Growth regulating agent	Zn-chitosan (Zn-CNPs)	Hameed *et al*., 2020
0	0	Stimulating germination and plant growth under non-stressed and stressed environments	Silk solution + trehalose and *Rhizobium tropici* Martínez-Romero *et al*. 1991 grown in Lysogeny broth (LB) + *Phaseolus vulgaris* L.	Mhada *et al.*, 2021
0	0	Seedling pots	Cotton + newspaper + corrugated cardboard + polycotton	Juanga-Labayen and Yuan, 2021
0	0	Growth stimulant	N-acetylated (10 %) + chitosan (CHT) + 6-benzylaminopurine (BAP) + kinetin (KIN)	Premi *et al*., 2021
0	0	Biofungicide and seed germination	Neem oil + Tween 20 + high-methoxyl pectin (HMP) + ultrapure water + high-methoxyl pectin (HMP) + Polymer L232	de Castro e Silva *et al*., 2019
0	0	Biostimulant for seed germination and increased seedling growth rate	Nanocomposites of HS/Ag	Dolmaa *et al.*, 2018
0	0	Biocontrol and biostimulant	*Pseudomonas fluorescens* Migula 1895 (Approved Lists 1980) + *Rhizobium* spp. + phosphorus solubilizing bacteria (PSB) + bio-friendly polymer + sugar syrup	Jagadeesh *et al*., 2019

Table 4. H index of principal authors on renewable alternative materials for seed protection.

Author and reference	Total of publications	Total of citations	H index	Year first published
Abbas HK (Accinelli *et al.*, 2016; 2018a; 2018b; 2020)	4	59	3	2016
Accinelli C (Accinelli *et al.*, 2016; 2018a; 2018b; 2020)	4	59	3	2016
Shier WT (Accinelli *et al.*, 2016; 2018a; 2018b; 2020)	4	59	3	2016
Little NS (Accinelli *et al.*, 2016; 2018a; 2020)	3	45	2	2016
Rahman M (Rahman *et al.*, 2018; Zohara *et al.*, 2019)	2	43	2	2018
Hameed A (Hameed *et al.*, 2020)	1	1	1	2020
Islam MT (Rahman *et al.*, 2018; Zohara *et al.*, 2019)	2	43	2	2018
Kotowicz JK (Accinelli *et al.*, 2016, 2018a)	2	44	2	2016
Lanzuise S (Carillo *et al.*, 2020; D'Errico *et al.*, 2020)	2	19	2	2020
Malinconico, M. (D'Errico *et al.*, 2020; Schettini *et al.*, 2013)	2	51	2	2013

Authors

Researchers with the highest number of publications in the field in the last 14 years were: Abbas HK, Accinelli C, and Shier WT, each with four documents and H index values of 3 and 59 times cited (Table 4). The H index indicates an estimate of the importance, significance, and broad impact of a scientist's cumulative publications (Hirsch, 2005). Lotka's law revealed that the frequency of publication by researchers was still low, with 93.7 % of the authors having only written one document. The evidence suggests that the scientific community has not paid enough attention to the development and utilization of alternative materials to improve germination, growth, crop yield, and physical and phytosanitary protection of seeds and seedlings.

Countries

Considering scientific production, the result was a network with 33 countries organized into 17 clusters based on total link strength. This weight attribute represents the collaboration level between countries (Sajovic and Boh, 2022) (Table 5). The United

Table 5. International co-authorship network on renewable alternative materials for seed protection.

Cluster	Country	Documents	Citations	Total link strength
2	United States	14	306	10
2	Bangladesh	2	43	2
9	Italy	10	139	5
3	India	6	158	3
1	Germany	2	49	2
1	Spain	2	83	2
1	Thailand	3	58	1
5	Russian Federation	3	7	2
6	Egypt	3	77	1
8	Iran	4	48	1
13	China	5	131	0
16	Poland	4	15	0

States was part of the cluster with the highest association strength (10) and contributed with 14 publications and 306 citations, followed by Italy with 10 publications and 139 citations. China received 131 citations with only five articles, with one research paper on a TMV biocontrol agent receiving 68 citations (Jia *et al.*, 2016). These results suggest that collaborative work in this line of research is still developing.

CONCLUSIONS

Because reducing world hunger is a global concern, the scientific community is actively working to propose agribusiness solutions that benefit the entire supply chain. This review with meta-analysis discusses the current state of knowledge and development of seed conservation; according to the h-index, the number of citations is not greater than the number of articles published by each author; according to Lotka's law, 94 % have published only one article; finally, over 14 years, only an average of 4 articles per year have been published. The results show that production and collaboration between researchers and countries in developing countries on new materials to improve seed quality are still incipient. Individual production and global, interdisciplinary collaboration are required to develop, test, and apply new and existing materials that improve quality while reducing contamination and raw material depletion. This study has two limitations: firstly, the information was extracted from only two databases (SCOPUS® and Web of Science™); secondly, due to lack of clarity and duplication of concepts, the establishment of keywords was extensive, resulting in 4558 articles, only 61 of which contributed to answering the research questions. The most cited and prolific authors were Abbas HK, Accinelli C, and Shier WT. The United States of America was the country with the largest number of publications (14). The most recently used keywords were "chitosan", "biopolymer", "seed coating", "maize", "seed treatment", and "sustainable agriculture". The most widely documented developments were biostimulants, biocontrol, containers, and protective drought agents. More research is needed to collect information from other databases and gray literature, as the production of articles in the world changes on a daily basis.

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Agrociencia

REVISIÓN DE ALCANCE SOBRE MATERIALES RENOVABLES ALTERNATIVOS PARA MEJORAR LA CALIDAD DE LAS SEMILLAS

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RESUMEN

El objetivo de esta revisión fue analizar y sintetizar las investigaciones publicadas sobre materiales alternativos renovables para mejorar la calidad de las semillas con el fin de reducir la contaminación y el agotamiento de las materias primas. El análisis se centró en la productividad por países y autores, así como en las palabras clave más relevantes. Los artículos se seleccionaron de las bases de datos SCOPUS® y Web of Science™, con actualizaciones hasta noviembre de 2021. Posteriormente, se analizaron mediante indicadores bibliométricos utilizando el VOS Viewer v.1.6.15 y el software BIBLIOMETRIX v.3.0. Los resultados muestran una baja producción científica global, con un total de 61 publicaciones; el mayor número de publicaciones aparece en 2020, con trece informes científicos. Los autores más citados y prolíficos fueron Abbas HK, Accinelli C y Shier WT. Estados Unidos fue el país con más publicaciones (14). Las palabras clave más utilizadas recientemente fueron “quitosano”, “biopolímero”, “recubrimiento de semillas”, “maíz (*Zea mays* L.)”, “tratamiento de semillas” y “agricultura sostenible”. Los avances más documentados fueron los bioestimulantes, el biocontrol, los contenedores y los agentes protectores contra la sequía. La colaboración interdisciplinaria podría promover el descubrimiento de nuevos materiales derivados de fuentes renovables que tengan un impacto significativo en la calidad de las semillas.

Palabras clave: tratamiento, protección, revestimiento, apósito, análisis bibliométrico.

INTRODUCCIÓN

Para resistir condiciones adversas como el ataque de hongos e insectos, las semillas suelen protegerse con insecticidas, fungicidas, películas de recubrimiento y otros polímeros, que también contribuyen a modificar sus características físicas, como la permeabilidad, el tamaño y la forma. Debido al agotamiento de las materias primas y a la contaminación generada por algunos agroquímicos y materiales, varios autores y empresas han propuesto materiales alternativos renovables para mejorar la calidad de las semillas, como la quitina y el quitosano para mejorar la germinación y el crecimiento (Rahman *et al*., 2018), el vermicompostaje y la harina de soja para estimular el crecimiento y el desarrollo (Amirkhani *et al*., 2019), bioplásticos para el recubrimiento de semillas para reducir el polvo (Accinelli *et al*., 2016; 2018b), *Aspergillus flavus* como biocontrol de la producción de aflatoxinas (Accinelli *et al*., 2018a), nanopartículas de quitosano y cobre para potenciar las respuestas de defensa (Choudhary *et al*., 2017; Divya *et al*., 2020); y biocompuestos basados en bacterias para estabilizar la rizosfera circundante (Hussain *et al*., 2019). Se han propuesto otros materiales para potenciar el desarrollo de plantas y plántulas, como los residuos de tomate reciclados y las fibras de cáñamo para macetas biodegradables (Schettini *et al*., 2013).

Se desconoce el avance global de estudios sobre el uso y desarrollo de materiales alternativos renovables para la protección de semillas y la promoción de la germinación; una revisión de alcance puede actualizar la extensión del tema y consiste en recopilar información seguida de un análisis bibliométrico (Verdejo *et al*., 2021). El uso de indicadores bibliométricos permite una evaluación objetiva y medible basada en datos cuantitativos (Flores-Fernández y Aguilera-Eguía, 2020), permitiendo inferir tendencias de investigación con el tiempo y detectar investigadores e instituciones más prolíficos, presentando así, una " perspectiva general" del tema (Aria y Curcurullo, 2017).

Las leyes bibliométricas se refieren a aquellas expresiones estadísticas utilizadas para describir el funcionamiento de la ciencia por medios matemáticos, entre las que destaca la ley de Lotka (Kumar, 2020). Este tipo de revisión aumenta el rigor metodológico y ayuda a desarrollar un conocimiento bien fundamentado mediante la acumulación de datos de la literatura existente, las tendencias y los problemas de la investigación actual (Verdejo *et al*., 2021) a través de un diseño reproducible para identificar, evaluar e interpretar los datos por la declaración PRISMA (Tricco *et al*., 2018). El análisis bibliométrico es una herramienta útil para medir y evaluar cuantitativa y cualitativamente la investigación científica (Sweileh, 2021) y comparar la conexión entre países, autores, volúmenes de investigación y la actividad de las instituciones para una mejor asignación de la financiación.

El software VOSviewer se utiliza en el análisis bibliométrico para estimar la fuerza de asociación entre dos elementos basándose en la distancia de separación, para lo cual se utiliza una técnica de optimización para formar conglomerados a partir de un conjunto de nodos estrechamente relacionados. La fuerza de asociación (s_{ij}) entre dos términos, i y j, se calcula con lo siguiente (van Eck y Waltman, 2009):

$$s_{ij} = \frac{c_{ij}}{w_i \, w_j}$$

donde c_{ij} denota el número de co-ocurrencias de los elementos i, j, w_i y w_j denotan el número total de ocurrencias de los elementos i y j, respectivamente, o el número total de co-ocurrencias de estos elementos. Por lo tanto, el término c_{ij} es el número de co-ocurrencias entre los artículos i y j. Se citan detalles sobre los métodos de mapeo, normalización y agrupación de VOSviewer (van Eck y Waltman, 2009; Waltman *et al*., 2010).

El presente estudio pretende analizar y sintetizar las investigaciones publicadas sobre materiales alternativos renovables para mejorar la calidad de las semillas con el fin de reducir la contaminación y el agotamiento de las materias primas. Esta investigación se centra en describir las principales características de los documentos pertinentes, así como las conexiones entre países, autores y temas emergentes.

Para cumplir el objetivo, establecimos una serie de preguntas de investigación (RQ): (RQ1) ¿Cómo ha progresado la investigación en el área de estudio en términos de publicaciones científicas y citas? (RQ2) ¿Qué materiales derivados de fuentes renovables se han desarrollado para la mejora de las semillas? (RQ3) ¿Quiénes son los investigadores con más publicaciones científicas? ¿Qué efecto tuvo su cita? (RQ4) ¿Qué país tiene la producción más destacada de artículos científicos relacionados con el tema de estudio?

MATERIALES Y MÉTODOS

Revisión de alcance

Las cinco fases siguientes siguieron la propuesta de Arksey y O'Malley (2005): definición de la pregunta o preguntas de investigación; identificación de todos los estudios pertinentes; selección de los estudios pertinentes; conformación de los datos; recopilación, resumen y comunicación de los resultados. Se tuvieron en cuenta dos criterios de inclusión: sólo se consideraron documentos como "artículos de investigación", sin limitaciones en cuanto al año de publicación o el idioma; sólo se incluyeron trabajos centrados en el desarrollo de materiales alternativos para mejorar la germinación, el crecimiento, el rendimiento de los cultivos y la protección física y fitosanitaria de semillas y plántulas.

La búsqueda bibliográfica se realizó utilizando las bases de datos SCOPUS® y Web of Science ™, estas bases de datos son la fuente digital más completa de artículos científicos con revistas revisadas por pares con rigurosos criterios de selección de editores y las más utilizadas en el análisis bibliométrico (Sweileh, 2021). En primer lugar, se utilizaron conceptos generales para buscar artículos relacionados con materiales alternativos para semillas; posteriormente, se utilizaron conceptos más específicos para guiar la búsqueda dentro del área agrícola utilizando los operadores booleanos lógicos "AND" y "OR" (Maçaira *et al*., 2018).

Análisis bibliométrico

El análisis se realizó con la herramienta R para el software BIBLIOMETRIX 3.0 BIBLIOSHINY (Aria and Curcurullo, 2017) y la versión 1.6.14 de VOSviewer (van Eck y Waltman, 2009). BIBLIOSHNY se utilizó para calcular la ley de Lotka y el índice H tras obtener la producción científica anual y de los autores a lo largo del tiempo en términos de número de publicaciones. La ley de Lotka es una ley aproximada del cuadrado inverso en la que el número de autores que publican un determinado número de artículos es una proporción fija con respecto al número de autores que publican un único artículo (Elango y Rajendran, 2012). El índice H mide la amplia repercusión del trabajo de una persona evitando los inconvenientes de otros criterios. Proporciona una medida objetiva del impacto y la relevancia de las obras académicas de un autor (Hirsch, 2005). Indicadores bibliométricos de coautoría y co-ocurrencia con países y todas las palabras clave como unidad de análisis. En VOSviewer, se dio la misma importancia a la coautoría y a las citas de una publicación ("recuento fraccionado") independientemente del número de autores, citas o referencias (Perianes-Rodriguez *et al*., 2016).

RESULTADOS Y DISCUSIÓN

La búsqueda inicial por palabras clave arrojó 4558 referencias (Figura 1). Al final, quedaron 61 artículos en la matriz, que comprendían todos los documentos para el análisis bibliométrico.

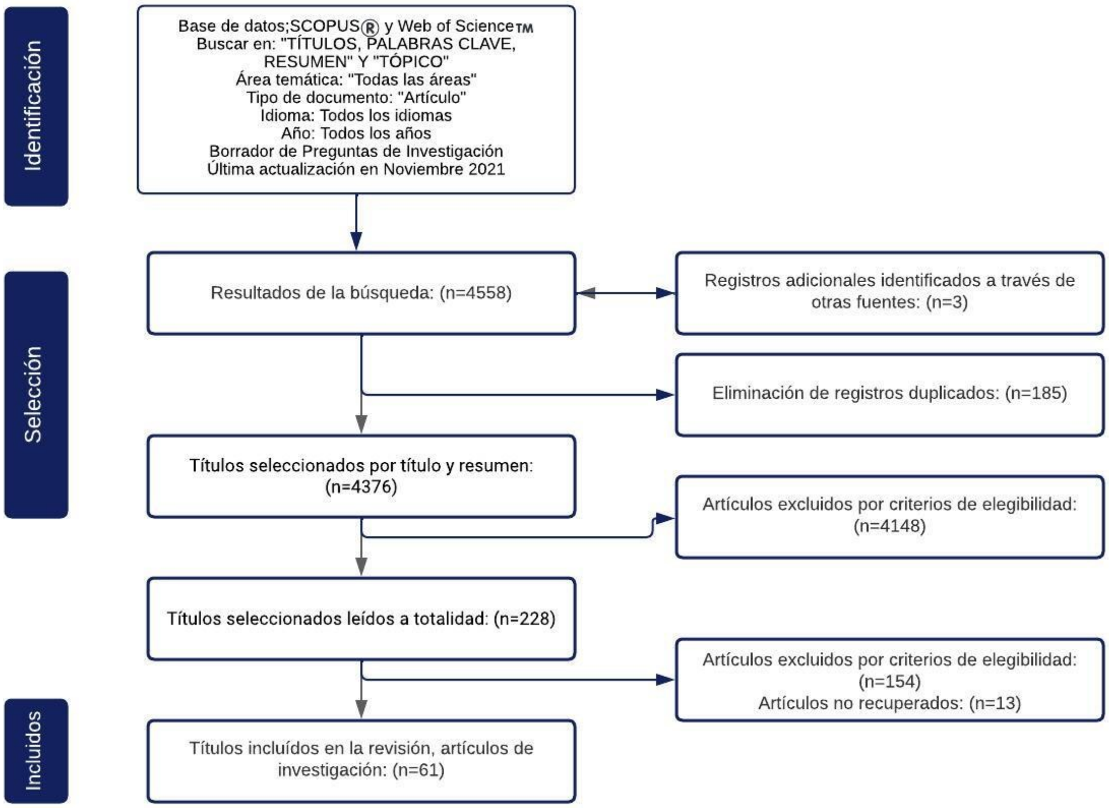

Figura 1. Etapas de la revisión de alcance de la literatura (modificado de Tricco *et al*., 2018).

Análisis bibliométrico descriptivo

Se publicaron 61 artículos entre 2007 y 2021 (Cuadro 1). Las revistas más influyentes fueron Crop Protection, Journal of Crop Improvement, PLOS One y Scientific Reports, con dos documentos, seguidas de Sustainable Chemistry and Engineering, Acta Agrobotanica, Acta Horticulturae y African Journal of Biotechnology (con un documento cada una). Por término medio, cada artículo ha sido citado 15 (14,66) veces, y fue escrito por cinco autores (4,92). El índice de colaboración (IC) fue de 5,12.

Cuadro 1. Información principal de artículos sobre materiales alternativos renovables para la protección de semillas.

Descripción del resultado	Resultados
Años de publicación	2007–2021
Ocurrencia de revistas	57
Número de documentos	61
Años entre cada publicación (promedio)	4.59
Número de citas por artículo (promedio)	14.66
Número anual de citas por documento (promedio)	2.59
Número total de referencias	2607
Artículos de investigación	60
Fe de erratas	1
Número de frases que aparecen con frecuencia en el título de las referencias de un artículo	754
Número de palabras clave	232
Número de autores	300
Artículos con un solo autor	3
Artículos de autores múltiples	297
Número de documentos por autor (promedio)	0.20
Número de autores por documento (promedio)	4.92
Número de coautores de cada artículo	5.38
Índice de colaboración	5.12

Producción científica

Las citas de publicaciones sobre materiales de protección de semillas y plántulas han aumentado gradualmente con el tiempo (Figura 2). Esto puede estar relacionado con la reciente preocupación por la preservación del medio ambiente y la reducción de la pérdida y el desperdicio de alimentos.

Materiales alternativos renovables y sus aplicaciones

La co-ocurrencia de redes bibliométricas dio como resultado un total de 183 palabras distribuidas en 14 agrupaciones (Cuadro 2). Las palabras clave con mayor ocurrencia y fuerza de enlace total que indican el número de publicaciones cuando dos palabras clave ocurren juntas (Guo *et al*., 2019) fueron quitosano, biopolímero, recubrimiento de semillas, maíz (*Zea mays* L.), tratamiento de semillas, agricultura sostenible, crecimiento y arroz (*Oryza sativa* L.) (Figura 3). Las palabras clave más utilizadas recien-

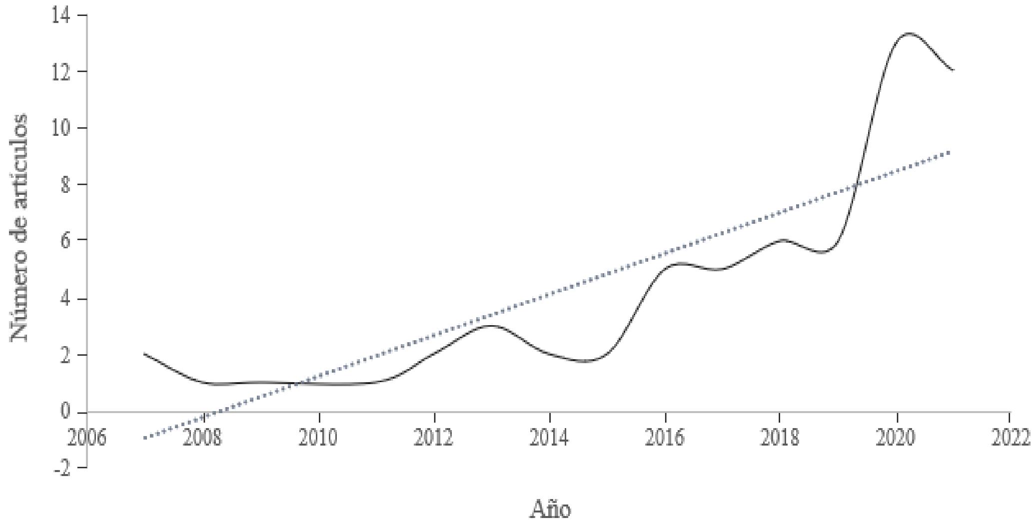

Figura 2. Documentos publicados entre 2007 y 2021 sobre materiales alternativos renovables para la protección de semillas.

Cuadro 2. Red de co-ocurrencia para palabras clave unitarias sobre materiales alternativos renovables para la protección de semillas.

Agrupación	Palabras clave	Ocurrencia	Fuerza total de enlace	Año promedio de publicación
13	Quitosano	8	8	2018
	Antioxidante	2	2	2020
5	Biopolímero	5	5	2018
	Bioagente	2	2	2020
	Bioacondicionamiento de semillas	1	1	2021
7	Recubrimiento de semillas	5	5	2017
	Agricultura sostenible	3	3	2020
	Biomateriales en la agricultura	1	1	2021
	Seguridad alimentaria	1	1	2021
1	Maíz (*Zea mays* L.)	4	4	2018
	Tratamiento de semillas	3	3	2017
6	Crecimiento	3	3	2016
	Arroz (*Oryza sativa* L.)	3	3	2013
8	Crecimiento de plantas Bacterias promotoras (pgpr)	3	3	2015
	Bacterias fijadoras de nitrógeno (microorganismos)	2	2	2019
	Conductancia estomática de la hoja	1	1	2021
12	Ajowan (*Carum copticum* L.)	2	2	2016
	Estrés salino	2	2	2020

Cuadro 2. Continue.

Agrupación	Palabras clave	Ocurrencia	Fuerza total de enlace	Año promedio de publicación
3	Control biológico	2	2	2009
	Rhizoctonia solani J.G. Kühn 1858	2	2	2015
10	Regulador de crecimiento vegetal	2	2	2019
	Salinidad	2	2	2015
2	Biocarbón	2	2	2018
	Metal pesado	2	2	2018
	Toxicidad de níquel	1	1	2021
	Estrés oxidativo	1	1	2021
4	Oligosacárido de quitina	2	2	2019
	Plasma de haz de electrones	2	2	2020
	Bioestimulantes vegetales	1	1	2021
11	Germinación de semillas	2	2	2020
	Producción de hojas	1	1	2021
	Alargamiento de brote	1	1	2021
9	Carboximetil celulosa	2	2	2017

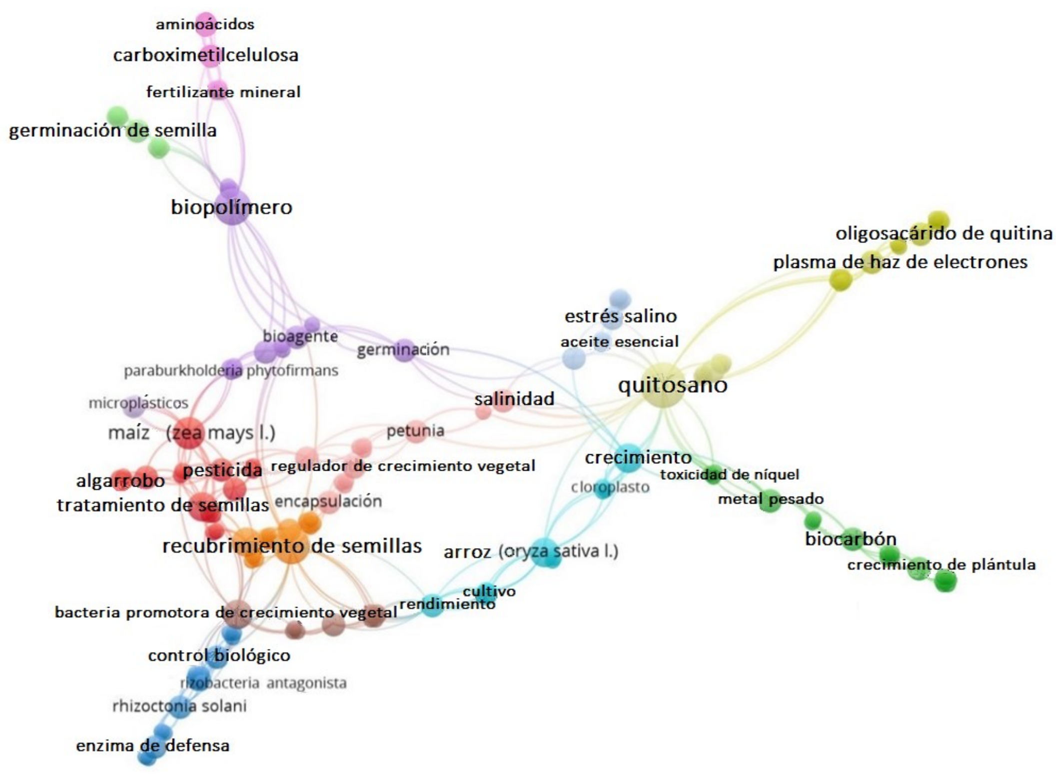

Figura 3. Agrupaciones de palabras clave sobre materiales alternativos renovables para la protección de semillas basadas en la fuerza y frecuencia de su asociación.

temente fueron las relacionadas con los biomateriales en la agricultura, la seguridad alimentaria, los bioestimulantes vegetales, la bioacondicionamiento de semillas y el cuidado, incluida la producción de hojas, el alargamiento de brotes, la conductancia estomática de las hojas, la toxicidad del níquel y el estrés oxidativo (Figura 4).

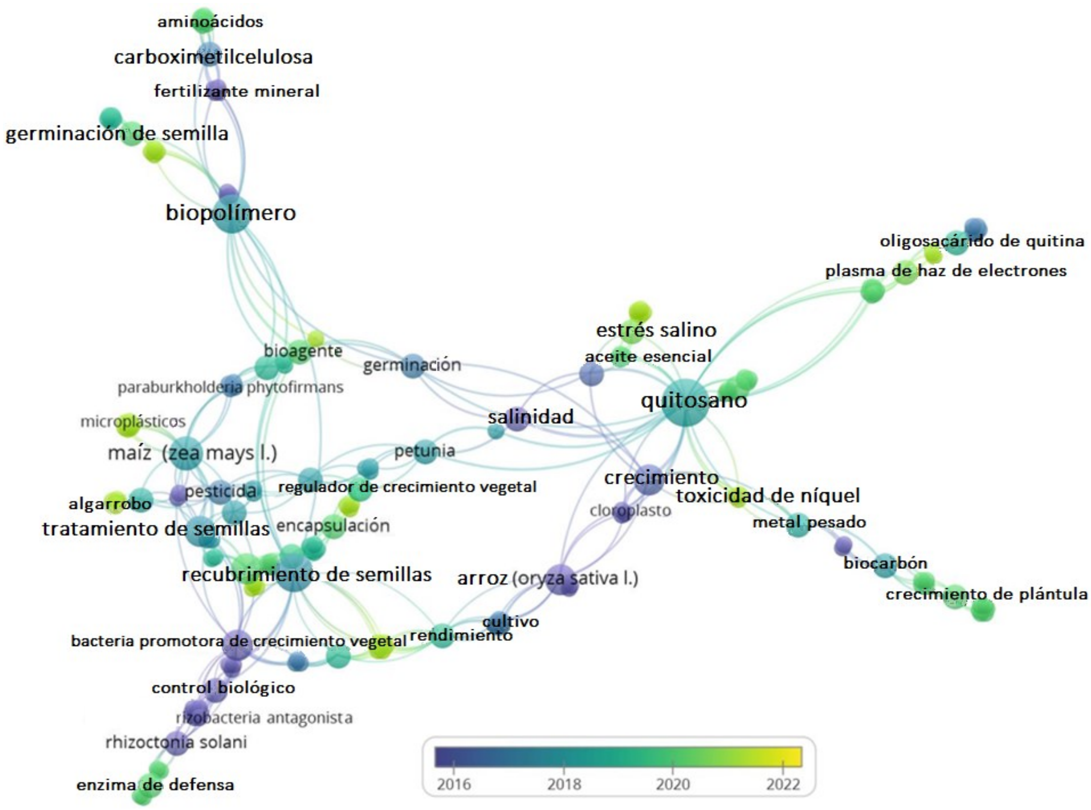

Figura 4. Red bibliométrica que muestra el lapso temporal de aparición de palabras clave sobre materiales alternativos renovables para la protección de semillas.

Los artículos se ordenan de mayor a menor de acuerdo con el número de citas (Cuadro 3). Choudhary *et al.* (2017), con un artículo de investigación sobre bioestimulantes y biocontrol, ocupó el primer lugar con 105 citas, aproximadamente 17 por año, sobre la aplicación de nanopartículas (NPs) de Cu-Quitosano contra la enfermedad de la mancha foliar de *Curvularia lunata* (Wakker) Boedijn 1933 en semillas de maíz. En esta revisión se analizó el uso de quitosano y quitina en diversas formas: oligosacárido de quitosano (COS) en el biocontrol contra el *Tobbacco Mosaic virus* (TMV) (Jia *et al*., 2016) y nanopartículas de quitosano (ChNP) contra el patógeno del tizón de la vaina (ShB) (Divya *et al.*, 2020). La quitina, como promotor del crecimiento vegetal en semillas de *Arabidopsis thaliana* (L.) Heynh., aumentó el peso fresco (10 %) y la longitud de la radícula (25 %) (Winkler *et al*., 2017). El quitosano oligomérico aumentó el peso fresco

Cuadro 3. Aplicaciones de materiales alternativos renovables para la protección de semillas.

Total de citas	Citas por año	Aplicación	Material	Referencia
105	17.5	Biocontrol y bioestimulante	NPs de Cu-quitosano + quitosano + CuSO4 + fungicida comercial (Bavistin)	Choudhary *et al*., 2017
68	9.7	Agente de biocontrol	Oligosacárido de quitosano	Jia *et al*., 2016
49	4.9	Macetas biodegradables que mejoran el rendimiento agronómico de los cultivos	Alginato de sodio + fibras naturales de cáscaras y hebras de cáñamo	Schettini *et al*., 2013
48	8	Biostimulante	Quitina	Winkler *et al*., 2017
44	2.7	Agente de biocontrol para *Aspergillus niger*	*Paenibacillus polymyxa* (Prazmowski 1880) Ash *et al*. 1994	Haggag, 2007
41	8.2	Biostimulante	Quitosano	Rahman *et al*., 2018
41	5.1	Promotor de crecimiento vegetal	Quitosano oligomérico y polimérico	Chamnanmanoontham *et al*., 2014
36	5.1	Compensación de la fitotoxicidad de las nanopartículas metálicas	Sustancias poliméricas extracelulares (EPS)	Li *et al*., 2016
35	5	Bioestimulante para la germinación	Biocarbón I (mezcla de tamices de madera procedentes de la producción de astillas), Biocarbón II (mezcla de lodos de papel y cáscaras de trigo) y Biocarbón III (lodos de depuradora).	Gascó *et al*., 2016
34	3.4	Cebado de semillas para mejorar la germinación, el crecimiento y aliviar el estrés abiótico	Ácido acético + quitosano	Mahdavi y Rahimi, 2013
31	5.2	Mejorar el rendimiento agronómico de los cultivos	Bacteria diazotrófica (*Azospirillum brasilense* cepa Ab-V5) + matriz de biopolímero	Oliveira *et al*., 2017
30	2.8	Actividad nematicida	Quitosano	Khalil y Badawy, 2012
27	3.9	Recubrimiento de semillas	*Trichoderma harzianum* Rifai 1969, anamórfico, cepa T-22 (ATCC 20847) + insecticida (imidacloprid) + fungicida (metalaxil-M+estrella)	Accinelli *et al*., 2016
21	7	Mejora de la germinación y el crecimiento de las plantas en presencia o ausencia de un hongo patógeno (*Fusarium oxysporum* Schltdl. 1824)	Acetato de celulosa + gelatina de piel porcina + ácido acético (695092, reactivo ACS), Tween® 80 + nanopolvo de óxido de cobre (II) + acetato de cobre monohidratado	Xu *et al*., 2020
20	6.7	Efecto estimulante sobre el crecimiento de plántulas	Biocarbón de paja de arroz (RS) y serrín de madera (WS)	Zhang *et al*., 2019

Cuadro 3. Continúa

Total de citas	Citas por año	Aplicación	Material	Referencia
19	6.3	Antimicótico para la aflatoxina B1 (AFB1)	Quitosano + sodio-tripolifosfato + diclorometano (DCM) + ácido acético glacial (GAA) + dimetilsulfóxido (DMSO) + metilglioxal (MG) + ácido perclórico + Tween-20 + Tween-80 + gel de sílice + etanol + metanol + 2, 2-difenil-1-picrilhidrazilo (DPPH) + ácido 2,2′-azino-bis (3-etilbenzotiazolina-6-sulfónico) + sal diamónica (ABTS)+ PDA y SMKY	Kumar *et al.*, 2020
18	1.5	Agente de biocontrol y biofertilizante	Microcápsula de *Bacillus subtilis*	Hernández-Suárez *et al.*, 2011
18	6	Cebado de semillas para estimular el crecimiento y el biocontrol de plagas	Quitosano	Jogaiah *et al.*, 2020
17	5.7	Biostimulante	*Trichoderma harzianum* Rifai 1969, cepa T22 + biopolímero (carboximetilcelulosa y Pluronic)	Carillo *et al.*, 2020
17	3.4	Biocontrol mediante recubrimiento de semillas	Almidón con pesticidas (insecticida: imidacloprid; fungicida: metalaxil-M) y esporas de *Aspergillus flavus* NRRL 30797 no aflatoxigénico + quitina + glicerol	Accinelli *et al.*, 2018b
16	1	Quitosano para la sequía y la recuperación del rendimiento vegetal	Ácido acético + quitosano	Boonlertnirun *et al.*, 2007
14	2.8	Biocontrol y bioestimulante mediante recubrimiento de semillas	Almidón de maíz modificado + quitina + glicerol + insecticida + fungicida	Accinelli *et al.*, 2018a
12	3	Bioestimulantes de recubrimiento de semillas, biopesticidas y biofertilizantes para mejorar el rendimiento y fortalecer las plántulas	Poli(alcohol vinílico) (PVA) y poli(vinilpirrolidona) (PVP) + glicerol + canola (*Brassica napus* L. cv. Faisal canola (RBN-03060)]. + *Bacillus subtilis* NH-100 + cepas fúngicas (*Macrophomina phaseolina* (Tassi) Goid. 1947, *Rhizoctonia solani* J.G. Kühn 1858, y *Fusarium oxysporum* Schltdl. 1824)	Hussain *et al.*, 2019
11	1.1	Semillas encapsuladas	Alginato de sodio + cloruro de calcio	Sakhanokho *et al.*, 2013
10	1.7	Biostimulante	Goma arábiga + carboximetilcelulosa (CMC) + dextrano + gelatina + glicerol + saponina + xantano + alginato, lecitina de huevo, lecitina de soja, leche desnatada + quitosano (grado alimentario) + aceite de ricino.	Bejarano *et al.*, 2017

Cuadro 3. Continúa

Total de citas	Citas por año	Aplicación	Material	Referencia
10	3.3	Bioestimulante para mejorar la tolerancia de las plantas al estrés oxidativo bajo salinidad	NaCl + quitosano + ácido acético + medio nutritivo Murashige y Skoog (MS)	Razavizadeh *et al.*, 2020
10	2.5	Bioestimulante de recubrimiento para la germinación y el crecimiento de las semillas	Vermicompostaje micronizado + harina de soja desgrasada + proteína vegetal + tierra de diatomeas (DE) + goma xantana (XG)	Amirkhani *et al*., 2019
8	1.1	Recubrimiento de semillas para mejorar el establecimiento de plantas autóctonas	Biocarbón de troncos de pino ponderosa (*Pinus ponderosa* Douglas ex C. Lawson) y lodgepole (*Pinus contorta* Douglas ex Loudon)	Williams *et al*., 2016
7	0.5	Cebado de semillas para mejorar la germinación, el biocontrol y el manejo de la enfermedad del mildiú velloso del mijo perla	Biopolímeros de goma + metalaxil (Apron 35 SD)+ metil-N-(2-metoxiacetíl)-N-(2,6-xilil)-DL-alaninat	Sudisha *et al*., 2009
7	1.4	Estimulador del crecimiento	Quitosano	Krupa-Małkiewicz y Fornal, 2018
7	3.5	Promotor de la germinación de semillas	Quitosano + sal sódica de ácido algínico + tripolifosfato sódico (STPP) + nanopolvo de óxido de cobre(II)	Leonardi *et al.*, 2021
7	2.3	Biofungicida	Quitosano-hexaconazol-dazomet	Maluin *et al.*, 2020
6	1.5	Germinación y bioestimulante	Bioaceite derivado de biomasa de algas *Macrocystis pyrifera* L.	Sankaranarayanan *et al.*, 2019
5	0.6	Bioestimulador	Chitosán	Salachna *et al.*, 2015
5	0.8	Bandejas de plántulas biodegradables que mejoran la calidad de las plántulas	PLA (ácido poliláctico)	Shi *et al.*, 2017
4	1	Biocontenedor para cultivos	Fibras de *Posidonia oceanica* L. + poli(3-hidroxibutirato-co-3-hidroxivalerato) + acetil tributil citrato + carbonato cálcico	Balestri *et al.*, 2019
4	1.3	Estimulante de la germinación de semillas y la producción de biomasa	Quitosano + lignocelulosa de coníferas	Vasilieva *et al.*, 2020
3	0.3	Reducir las micotoxinas de Fusarium	Biopolímeros de b-d-glucano	El-Naggar y Thabit, 2014
3	1.5	Promotor de germinación de semillas	Quitooligosacárido (COS)	Vasilieva *et al*., 2021

Cuadro 3. Continúa

Total de citas	Citas por año	Aplicación	Material	Referencia
3	1	Biocontrol de la ShB causada por *Rhizoctonia solani* J.G. Kühn 1858	Quitosano + ácido acético	Divya *et al.*, 2020
2	0.2	Estimular la germinación y el crecimiento vegetal	Goma xantana + sal sódica de carboximetilcelulosa + fertilizantes + micronutrientes	Struminska *et al.*, 2014
2	0.2	Protección de semillas y plántulas y estimulación del crecimiento	Quitosano + hemicelulosas (galactoglucomananos)	Niekraszkiewicz *et al.*, 2012
2	1	Mejora de la tolerancia de la soja a la toxicidad del Ni	Quitosano	Sadeghipour, 2021
2	1	Bioacondicionamiento de semillas	Alginato de sodio + carboximetilcelulosa + goma arábiga + goma xantana + *Trichoderma asperellum* Samuels, Lieckf. & Nirenberg 1999	Chin *et al.*, 2021
2	1	Biocontrol	Biopolímero de la leguminosa *Ceratonia siliqua L.* + *Trichoderma harzianum* Rifai 1969, M10 + *Trichoderma atroviride* Bissett 1984, P1 + *Trichoderma longibrachiatum* Rifai 1969, MK1	D'Errico *et al.*, 2020
2	0.7	Herbicidas naturales a base de aceites esenciales	Aceite esencial (EO) de ajedrea (*Satureja hortensis* L.) + polímeros naturales (es decir, goma arábiga/gelatina (AGG), pectina de manzana (AP), gelatina (G)).	Taban *et al.*, 2020
2	0.7	Agente antisequía	Oligosacárido de quitosano	He *et al.*, 2020
2	0.5	Bioestimulante para la germinación y el crecimiento de las plántulas, biopesticida	Quitosano	Zohara *et al.*, 2019
1	0.7	Germinación y vigor de semillas	Fungicida químico (CA) + polímeros fungicidas biológicos (polímero de quitosano-lignosulfonato (CL) y eugenol incorporado al polímero de quitosano-lignosulfonato (E+CL))	Thobunluepop *et al.*, 2008
1	0.2	Biocontenedor	90 % de ácido poliláctico (PLA) y 10 % de lignina, 60 % de PLA y 40 % de polímero de soja con anhídrido adípico	Flax *et al.*, 2018
1	0.5	Efecto estimulante para la germinación	Quitosano + alginato/PEG + inoculante comercial (HiStick® Soy)	Jarecki, 2021
1	0.5	Biocontrol para *Arabidopsis thaliana* (L.) Heynh. contra la salinidad	Bentonita y l-prolina	Merino *et al.*, 2021

Cuadro 3. Continúa

Total de citas	Citas por año	Aplicación	Material	Referencia
1	0.5	Efecto estimulante para la germinación y el crecimiento vegetal	Quitosano+alginato con PGR (reguladores del crecimiento vegetal)	Vlahoviček-Kahlina *et al.,* 2021
1	0.5	Minimización de pérdidas por abrasión	Sepiret (BASF, Ludwigshafen Alemania) + bioplástico líquido a base de almidón + proteína de soja	Accinelli *et al*., 2020
1	0.3	Agente regulador de crecimiento	Zn-quitosano (Zn-CNPs)	Hameed *et al*., 2020
0	0	Estimular la germinación y el crecimiento de las plantas en entornos estresados y no estresados	Solución de seda + trehalosa y *Rhizobium tropici* Martínez-Romero *et al.* 1991 cultivadas en caldo de lisogenia (LB) + *Phaseolus vulgaris* L.	Mhada *et al*., 2021
0	0	Macetas para plántulas	Algodón + periódico + cartón ondulado + polialgodón	Juanga-Labayen y Yuan, 2021
0	0	Estimulante de crecimiento	N-acetilado (10 %) + quitosano (CHT) + 6-bencilaminopurina (BAP) + kinetina (KIN)	Premi *et al*., 2021
0	0	Biofungicida y germinación de semillas	Aceite de neem + Tween 20 + pectina de alto metoxilo (HMP) + agua ultrapura + pectina de alto metoxilo (HMP) + polímero L232	de Castro e Silva *et al*., 2019
0	0	Bioestimulante para la germinación de semillas y el aumento de la tasa de crecimiento de plántulas	Nanocompuestos de HS/Ag	Dolmaa *et al*., 2018
0	0	Biocontrol y bioestimulante	*Pseudomonas fluorescens* Migula 1895 (Listas aprobadas 1980) + *Rhizobium* spp. + bacterias solubilizadoras de fósforo (PSB) + polímero bioamigable + jarabe de azúcar	Jagadeesh *et al*., 2019

y seco de hojas y raíces en las semillas y plántulas de arroz (Chamnanmanoontham *et al*., 2014) y ajowan (*Carum copticum* (L.) Benth. & Hook. f. ex C.B. Clarke). Bajo estrés salino, el quitosano promovió el porcentaje y la tasa de germinación, el índice de vigor de las plántulas, la longitud, el peso seco y la formación de radículas (Mahdavi y Rahimi, 2013). La aplicación de quitosano foliar a plántulas de fresa aumentó el crecimiento y la producción de frutos, así como la concentración de antioxidantes totales, flavonoides, fenólicos, carotenoides y antocianinas (Rahman *et al*., 2018). Estos agentes se utilizaron en los cultivos por su importancia para la seguridad alimentaria y su alto valor añadido.

Otros desarrollos presentados (Cuadro 3) incluyen contenedores hechos de fibras naturales de cáscaras de cáñamo y hebras utilizadas para semillas de pimiento, que produjeron pelos radiculares muy densos y activos (Schettini *et al*., 2013). Una bandeja para plántulas hecha con ácido poliláctico (PLA) para plántulas de arroz provocó un aumento de la tasa de emergencia y un diámetro promedio de la raíz un 8.63 % mayor que el control (Shi *et al*., 2017). Los contenedores fabricados con fibras de *Posidonia oceanica* (L.) Delile "egagropili" proporcionaron protección para el crecimiento y anclaje a las plantas (Balestri *et al*., 2019). Estos biocontenedores mejoran la sostenibilidad medioambiental al reducir las pérdidas de semillas y plántulas.

Autores

Los investigadores con mayor número de publicaciones en este campo en los últimos 14 años fueron: Abbas HK, Accinelli C, y Shier WT, cada uno con cuatro documentos y valores del índice H de 3 y 59 veces citado (Cuadro 4). El índice H indica una estimación de la importancia, trascendencia y amplia repercusión de las publicaciones acumuladas de un científico (Hirsch, 2005). La ley de Lotka reveló que la frecuencia de

Cuadro 4. Índice H de autores principales sobre materiales alternativos renovables para la protección de semillas.

Autor y referencia	Total de publicaciones	Total de citas	Índice H	Año de primera publicación
Abbas HK (Accinelli *et al*., 2016; 2018a; 2018b; 2020)	4	59	3	2016
Accinelli C (Accinelli *et al*., 2016; 2018a; 2018b; 2020)	4	59	3	2016
Shier WT (Accinelli *et al*., 2016; 2018a; 2018b; 2020)	4	59	3	2016
Little NS (Accinelli *et al*., 2016; 2018a; 2020)	3	45	2	2016
Rahman M (Rahman *et al*., 2018; Zohara *et al*., 2019)	2	43	2	2018
Hameed A (Hameed *et al*., 2020)	1	1	1	2020
Islam MT (Rahman *et al*., 2018; Zohara *et al*., 2019)	2	43	2	2018
Kotowicz JK (Accinelli *et al*., 2016, 2018a)	2	44	2	2016
Lanzuise S (Carillo *et al*., 2020; D'Errico *et al*., 2020)	2	19	2	2020
Malinconico, M. (D'Errico *et al*., 2020; Schettini *et al*., 2013)	2	51	2	2013

publicación de los investigadores seguía siendo baja, ya que el 93.7 % de los autores sólo había escrito un documento. Las pruebas sugieren que la comunidad científica no ha prestado suficiente atención al desarrollo y la utilización de materiales alternativos para mejorar la germinación, el crecimiento, el rendimiento de los cultivos y la protección física y fitosanitaria de semillas y plántulas.

Países

Teniendo en cuenta la producción científica, el resultado fue una red con 33 países organizados en 17 agrupaciones basadas en la fuerza total de los vínculos. Este atributo de peso representa el nivel de colaboración entre países (Sajovic y Boh, 2022) (Cuadro 5). Estados Unidos formó parte de la agrupación con mayor fuerza de asociación (10) y contribuyó con 14 publicaciones y 306 citas, seguido de Italia con 10 publicaciones y 139 citas. China recibió 131 citas con solo cinco artículos, y un trabajo de investigación sobre un agente de biocontrol del TMV recibió 68 citas (Jia *et al.*, 2016). Estos resultados sugieren que el trabajo de colaboración en esta línea de investigación aún está en desarrollo.

Cuadro 5. Red internacional de coautoría sobre materiales alternativos renovables para la protección de semillas.

Agrupación	País	Documentos	Citas	Fuerza total de enlace
2	Estados Unidos	14	306	10
2	Bangladesh	2	43	2
9	Italia	10	139	5
3	India	6	158	3
1	Alemania	2	49	2
1	España	2	83	2
1	Tailandia	3	58	1
5	Federación rusa	3	7	2
6	Egipto	3	77	1
8	Irán	4	48	1
13	China	5	131	0
16	Polonia	4	15	0

CONCLUSIONES

Dado que reducir el hambre en el mundo es una preocupación global, la comunidad científica trabaja activamente para proponer soluciones agroindustriales que beneficien a toda la cadena de suministro. Esta revisión con metaanálisis analiza el estado actual de los conocimientos y el desarrollo de la conservación de semillas; de acuerdo con el índice h, el número de citas no es mayor que el número de artículos publicados por cada autor; según la ley de Lotka, el 94 % sólo ha publicado un artículo; por último, a lo largo de 14 años, sólo se ha publicado un promedio de 4 artículos al año. Los resultados muestran que la producción y la colaboración entre investigadores y países en desarrollo sobre nuevos materiales para mejorar la calidad de las semillas son aún incipientes. La producción individual y la colaboración global e interdisciplinaria son necesarias para desarrollar, probar y aplicar materiales nuevos y existentes que mejoren la calidad a la vez que reducen la contaminación y el agotamiento de las materias primas. Este estudio tiene dos limitaciones: en primer lugar, la información se extrajo de solo dos bases de datos (SCOPUS® y Web of Science™); en segundo lugar, debido a la falta de claridad y a la duplicación de conceptos, el establecimiento de palabras clave fue extenso, lo que dio como resultado 4558 artículos, de los cuales solo 61 contribuyeron a responder a las preguntas de investigación. Los autores más citados y prolíficos fueron Abbas HK, Accinelli C y Shier WT. Estados Unidos fue el país con mayor número de publicaciones (14). Las palabras clave más utilizadas recientemente fueron "quitosano", "biopolímero", "recubrimiento de semillas", "maíz", "tratamiento de semillas" y "agricultura sostenible". Los avances más documentados fueron los bioestimulantes, el biocontrol, los contenedores y los agentes protectores contra la sequía. Es necesario seguir investigando para recopilar información de otras bases de datos y de la literatura gris, ya que la producción de artículos en el mundo cambia a diario.

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