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Evolution of struvite research and the way forward in resource recovery of phosphates through scientometric analysis

Krishnamoorthy Nageshwari, Paramasivan Balasubramanian *

Department of Biotechnology & Medical Engineering, National Institute of Technology Rourkela, Odisha, 769008, India

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ABSTRACT

The alarming decline in phosphate raw materials and increase in eutrophication has escalated interest in struvite research. This manuscript presents scientometric analysis on struvite for fertilizing applications to comprehend the evolution and transformation of the field, investigate the existing challenges, research gaps, and developments to gain insights on the emerging trends for further studies. A total of 1550 scientific documents, between the years 1999–2020, were collected from Scopus® and PubMed® using an appropriate trail of keywords and analyzed using CiteSpace 5.7. R2. Ten attributes such as annual publication output and types, co-authorship network, co-occurring author keywords, the network of authors' countries and institutions, author co-citation network, document co-citation network, journal co-citation network, and co-occurring subject categories were investigated. Based on the distinct network patterns generated by the software, progress of the field, paradigm shifts, knowledge gaps, and scientific frontiers were identified and mapped. The literature on struvite research was found to have bloomed in the early 2000s and accelerated significantly until now, with maximum contribution from China and United States. Journal of cleaner production ranks 5th with 3.35% share of the total contribution according to journal co-citation analysis. Cluster analysis of co-occurring author keywords revealed the research progression through the expanse, knowledge gaps, disciplinary and inter-disciplinary advancements, and future exploration trends. The research has evolved from evaluating the process influencing parameters and developing suitable reactor designs to installation of pilot-scale plants for commercialization. However, lack of experiments on real-time wastewater, plant growth studies and the underlying nutrient uptake mechanisms persist as major research gaps. Focussing on these aspects along with integrated advanced technologies such as microbial fuel cells, microbial electrolysis cells, electrochemical precipitation of struvite and wider application of struvite can pave way for enormous progress of this field.

1. Introduction

Phosphorus is an essential nutrient necessary for the growth, health, and vigour of all plants. With the increase in population, the phosphate rocks are being exploited to produce commercial fertilizers and are expected to run out in the next 50–100 years (Van Kauwenbergh et al., 2013). On the other hand, nutrient-rich wastewaters are let into water bodies causing eutrophication and algal blooms, thus destroying the ecosystem underwater (Zou et al., 2020; Krishnamoorthy et al., 2020). These crises triggered the researchers to work on bringing a sustainable solution to close the phosphorus loop. In this regard, the interest and theoretical knowledge on struvite grew, considering its potential as a fertilizer. Struvite ($MgNH_4PO_4{\cdot}6H_2O$) is formed by bonding between magnesium, ammonium, and phosphate ions (Eq. (1)) under favorable conditions (Wu et al., 2018).

$$Mg^{2+} + NH_4^+ + PO_4^{3-} + 6H_2O \leftrightarrow MgNH_4PO_4.6H_2O \quad (1)$$

It can be seen from Eq. (1) that equimolar ratios of magnesium, ammonium and phosphate are required for the formation of struvite. Most of the wastewaters contain high concentration of phosphate and ammonium, and hence external supply of magnesium is essential for initiating struvite recovery. There are several mechanisms which can be employed for recovery including chemical precipitation, ion exchange, electrochemical and biomineralization. Spontaneous struvite precipitation also takes place with pre-existence of magnesium in the medium (Krishnamoorthy et al., 2020). The process is highly pH-dependant and

* Corresponding author.,
E-mail address: biobala@nitrkl.ac.in (P. Balasubramanian).
URL: http://orcid.org/0000-0002-3821-5029 (P. Balasubramanian).

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occurs with an alkaline pH varying between 7 and 11.5 (Kim et al., 2017). Mixing rate and supersaturation also plays a significant role in nucleation and development of struvite crystals. Other parameters that influence struvite recovery are temperature, co-existing ions, Mg: P molar ratio, hydraulic retention time, seeding and feeding sequence. The colour and nutrient composition of struvite slightly varies with usage of different wastewater sources and precipitation conditions. However, the degree of supersaturation defines the morphology and size of struvite crystals (Krishnamoorthy et al., 2020, 2021a). The structure of struvite as revealed X-ray diffraction crystallography (XRD) is orthorhombic with space group Pmn21 (Manzoor et al., 2018). It consists of prominent PO43-, Mg–O, NH4+ and H–O–H groups as shown by IR spectrums. The theoretical composition of struvite as per American Public Health Association (APHA) standards is 12.6, 9.9 and 5.7% of phosphate, magnesium and ammonium, respectively (Krishnamoorthy et al., 2021c). The size of the crystals ranges from 15 μm to 3 mm (Krishnamoorthy et al., 2021a). Isomorphous, irregular, sharp-edge, porous and course crystals with shapes varying between dendrite, tubular and rod-like were observed by various researchers (Karbakhshravari et al., 2020; Le Corre et al., 2007; Zhang et al., 2009).

The agronomic aspects of any fertilizer include the presence of essential nutrients, effective nutrient-release mechanisms, optimum dosage for plant growth and admissible heavy metal concentrations as per legal requirements. In case of struvite, phosphorus and nitrogen are the major portions present, as necessary for plant growth. Its low solubility ensures slow and appropriate release of phosphorus and ammonium into the soil over time. Struvite is regarded as a slow-release fertilizer due to its low solubility in polar solvents. Besides, it act as soil conditioners for both acidic and alkaline soils and contain the major essential plant nutrients in an accessible form (Robles-Aguilar et al., 2020). However, the low solubility of struvite was thought to be a limitation compared to high soluble phosphate fertilizers. Still, it is now regarded as a useful agronomic utility due to its slow-release property. Struvite application also helps in preventing the harmful overdose (Siciliano et al., 2020). Zhang et al. (2017) reported a recovery of 1 kg struvite from 100 m^3 of treated livestock wastewater. Plant growth studies conducted using struvite recovered from various wastewater and other commercial fertilizers show better yield and faster growth of crops with struvite. In experiments conducted by Yetilmezsoy and Sapci-Zengin (2009) for cultivation of garden cress (Lepidum sativum), portulaca (Portulaca oleracea) and grass (Lolium perenne) using struvite recovered from UASB treated poultry manure wastewater, a notable increase of 257% fresh and 402% dry weights, respectively, were obtained in comparison to KCl. Ryu et al. (2012a,b) reported 1.6 g struvite kg^{-1} soil to be optimum for growing Chinese cabbage. In another study, dosage of 2.85 g struvite kg^{-1} showed comparable results with commercial fertilizer containing NH_4NO_3 and KH_3PO_4; however, the optimum dosage was found to be 5.71 g struvite kg^{-1} for cultivation of tomato and corn plants (Uysal et al., 2014). As far as the heavy metal concentration is concerned, characterization results of struvite show very low content of heavy metals and other micropollutants compared to commercial, mineral and organic fertilizers as per the EU Fertilizing Products Regulation (2019/1009). Absence of heavy metal like cadmium, arsenic, lead and nickel, and lowest concentration of copper was observed in Chinese cabbage samples grown using struvite. Also, struvite use did not contribute to the increase in metal absorption in Spinacia Oleracea as compared to commercial fertilizer (Ryu et al., 2012a, b). Antonini et al. (2012) concluded urine derived struvite as a hygienically safe fertilizer with low heavy metal input to the agricultural field as per the German Fertilizer and Sewage Sludge Regulations and Federal Soil Protection Act. There are around 80 operational plants worldwide that are intended to recover phosphate from wastewater (Shaddel et al., 2019). Though several pot studies have been carried out using struvite, field scale application is still lacking due to insufficient awareness among people regarding the benefits and economic viability.

Struvite is highly suitable for acidic soils (pH < 6) as it dissolves in acid and yields high biomass. It can be precipitated from any wastewater rich in nutrients such as magnesium, phosphorus, and ammonium, which are the most essential macronutrients required by superior plants and various commercial crops. Many such wastewater sources are being explored in recent years with advancing technologies to improve struvite recovery. Struvite precipitation is also regarded as a means of removing recalcitrant nutrients from sludge. When produced in large quantities, the micropollutant burden in struvite can be significantly reduced for possible use as biosolids in soil. Upon acid secretion by plant roots, the nutrients in struvite slowly dissolve into ionic forms that can be readily assimilated by crops (Abel-Denee et al., 2018; Krishnamoorthy et al., 2021a, 2021b). Depending on the physicochemical conditions such as pH and ion concentrations of the wastewater under study (rural, industrial, urban etc.), formation of struvite analogues like K-struvite ($MgKPO_4$) and Na-struvite ($MgNaPO_4$) have been reported in literature (Huang et al., 2019; Perwitasari et al., 2017). These analogues also have enormous potential to be used as fertilizer are most suitable for soil deficient in potassium and sodium.

In recent years, struvite crystallization is being integrated with several biorefinery processes for enhancing sustainable and economic feasibility. Such a technique is a combined algal growth step to reduce the sludge organics while employing the biomass for biodiesel production and biofertilizer production (microalgal biochar, foliar spray etc.) for creating nexus between food, energy, and water (Bandara et al., 2020; Chavan and Mutnuri, 2020).

This paper provides a scientometric view on struvite research over the last two decades, focussing on the domain's progression, paradigm shifts, turning points, challenges, crises, and new approaches for encroachment. With the help of CiteSpace, visual networking patterns were generated for ten significant attributes such as publication outputs and types, co-authorship network, co-occurring author keywords, the network of authors' countries and institutions, author co-citation network, document co-citation network, journal co-citation network, and co-occurring subject categories that can qualitatively and quantitatively analyze the trends and dynamics of research with a thorough understanding of the disciplinary and inter-disciplinary approaches. The published literature data by scientific research communities were obtained from the Scopus® and PubMed® repositories. With this information, the software is tailored to reveal the contribution of authors, countries, institutions, and journals from a broad spectrum of perspectives on struvite research. Also, the visualization of a transient burst of documents aids in understanding the critical transition in research development, focus swing across domains, and potential paradigm shifts. The manuscript assesses different techniques developed to precipitate struvite since inception, the research gaps that need improvement, and emerging aspects for future studies. This script is the first and foremost bibliometric study conducted on struvite research with additional highlights on its commercial scenario across the globe. On the whole, this paper will assist in complete apprehension of the research patterns, scientific advances, evolving trends, and salient technologies developed for struvite crystallization over the years.

2. Methodology

2.1. Data collection

The data for the analysis were retrieved from the renowned Scopus® and PubMed® database. The repository was chosen based on the comprehensiveness and availability of a large dataset of Scientific, Technical, and Medical (STM) journals to assess the citation impact of authors, journals, and articles. Scopus and PubMed constitutes various research publications such as articles, review papers, book chapters, and conference proceedings. The data can also be retrieved in multiple file formats that are compatible with various data analysis software (Chen, 2016; Kipper et al., 2020). The key search topic was "struvite". However, to segregate papers that are more relevant to phosphorus recovery and fertilizing applications than medical, a set of keywords were opted based on the pre-literature review. The combination of terms including "(Struvite AND (phosphorus OR phosphate) AND recovery) OR (Struvite AND fertilizer)" was used to search for relevant data. These trails of words were arrived at after a series of iterations to eliminate inappropriate data. The records were considered pertinent and valid only if the terms were found to appear in either one or all of the following fields: Title, keywords, and abstract. The information was further confined for publications within 1999–2020, as they were considered the prime time between the blooming of research and the present scenario. Thus, this study systemically and systematically examines many research findings in the last two decades to analyze the evolution, significance, and emerging trends in the area of struvite crystallization.

2.2. Scientometric analysis

The refined data set was fed into CiteSpace software 5.7.R2 for bibliometric analysis. CiteSpace is a Java-based software that supports and analyses citations and references to visualize the trends and patterns in the scientific literature. The co-citation analysis theory and pathfinder network scaling use mathematical formulae to map the structures with similar research disciplines and frontiers. Using CiteSpace, options such as time slicing, text processing, node types, links, selection criteria, and pruning were adjusted to analyze ten scientometric indicators like annual publication trend, publication type, co-authorship network, co-occurring author keywords, the network of authors' countries, and institutions, author co-citation network, document co-citation network, journal co-citation network and co-occurring subject categories. The data obtained were utilized to construct networks to present details on various aspects of crystallization, such as growth fashion, research highlights, and development (Chen, 2016; Kamali et al., 2020).

2.3. Data interpretation

To proceed with the analysis and interpretation of data collected on struvite research, the scientometric structural and temporal metrics including betweenness centrality (BC), citation burst (CB), sigma, citation count (CC), citation frequency (CF), and clustering, were utilized. Betweenness centrality accounts for node characteristics in a network and quantifies the possibility of how a node bridges the paths around them. The nodes are part of the link between two arbitrary nodes of the extent. Its value varies between zero and one. A high centrality score indicates that it has a strong influence on the information flow and provides information on why two clusters are connected. This characteristic also helps to recognize the structural holes in a network to predict significant research aspects of various scientific communities. Also, it identifies the pivotal points between different specialties in an evolving network. Citation burst highlights the most active area (i.e., article, author, keyword, etc.) in a particular period and measures the citation quantity in that specific area. It denotes the rate of change or frequency at which an entity has been cited in a particular duration. A node with a substantial burst value signifies the work's impact and potential within a short time.

Sigma is a pre-defined parameter accounting for integrated strength of a node's structural and temporal characteristics (viz. betweenness centrality and citation burst). A high sigma value usually indicates a node's strategically important structural property and temporal implication. Citation count is a criterion that identifies the number of citations received by an entity (i.e., article, author, journal, etc.) over a certain period (exposure time). Citation frequency is calculated as the total number of citations received by an entity during a particular time divided by its exposure time. Clustering is a technique by which an entity's input data under analysis is divided into sub-categories based on similarity. The most substantial cluster represents the highest level of similarity and is denoted as "#0". The clusters' name is given based on the strong citation burstness of the most exciting work in that period (Chen, 2004, 2016; Wu et al., 2020; Kamali et al., 2020). The flowchart of the methodology used for the scientometric analysis of struvite research during 1999–2020 is shown in Fig. 1.

Some of the limitations of the study includes: data collected from the repositories is confined to the keywords used for data search. Hence, authors cannot ensure that complete set of articles published on struvite between 1999 and 2020 have been analyzed to comprehend various aspects of the field. Also, the article number could vary depending on the choice of repository. In addition, the scientometric indicators such as total number of publications and citations were used for obtaining scholarly contribution of researchers. However, inclusion of quartile index and negation of self-citations can provide real activity of the author. The scientometric indicators can be further diversified by involving silhouette value, modularity value, log-likelihood ratio etc. to arrive at further information regarding the reliability of the cluster network.

3. Results

After careful screening of the literature data, 1550 unique records were obtained from January 1999 to October 2020. These references were analyzed using CiteSpace for detecting and visualizing critical information and changes using ten scientometric indicators mentioned in section 2.3. The study's discoveries are expected to contribute to the current body of knowledge by emphasizing the trends of struvite research by clusters and mapping the network of crucial researchers, countries, institutions, and recommending areas for forthcoming studies.

3.1. Analysis of annual publication output

The literature revealed that the term "struvite" was introduced in the year 1961, where the author referred to it as an impurity formed during the production of liquid fertilizer from phosphoric acid (Slack and Nason, 1961). Though few articles had mentioned it in the later years, the field started to bloom only after 1999. After that, the number of publications considerably increased despite a few uncertainties in the initial years. Fig. 2a shows a stacked histogram comparing the number of documents published on struvite and articles specific to fertilizing applications. The growth trend explains the increasing interest, and progress in the field and the curve fits well in the second-order polynomial equation with an R^2 value of 0.93. The publication count reached its peak in 2019 with 170 records. There is a slight decrease in research documents during 2020 as the analysis was carried out on October 25, 2020, and the data includes publications until then.

3.2. Publication type analysis

The research communities' contribution was categorized as research articles, conference papers, reviews, book chapters, and others (conference reviews, short surveys, and notes). It can be seen from Fig. 2b that among all the bibliographic records gathered through the study period, research articles have secured the highest proportion of 82.2%, followed by conference proceedings (9.9%) and review articles (5%).

3.3. Co-authorship network

Author contribution analysis is a criterion to arrive at the most contributing authors on struvite research for fertilizer application. The results of the study are shown in Fig. 3a. So far, around 1316 authors have contributed to various aspects of struvite research. The figures represent the authors' network and their collaboration along the period of study. The size node correlates with the number of publications, and the links denote their co-authorship. The thickness of the links and proximity of the nodes defines the strength of co-operation between the authors. The clusters present outside the leading network domain

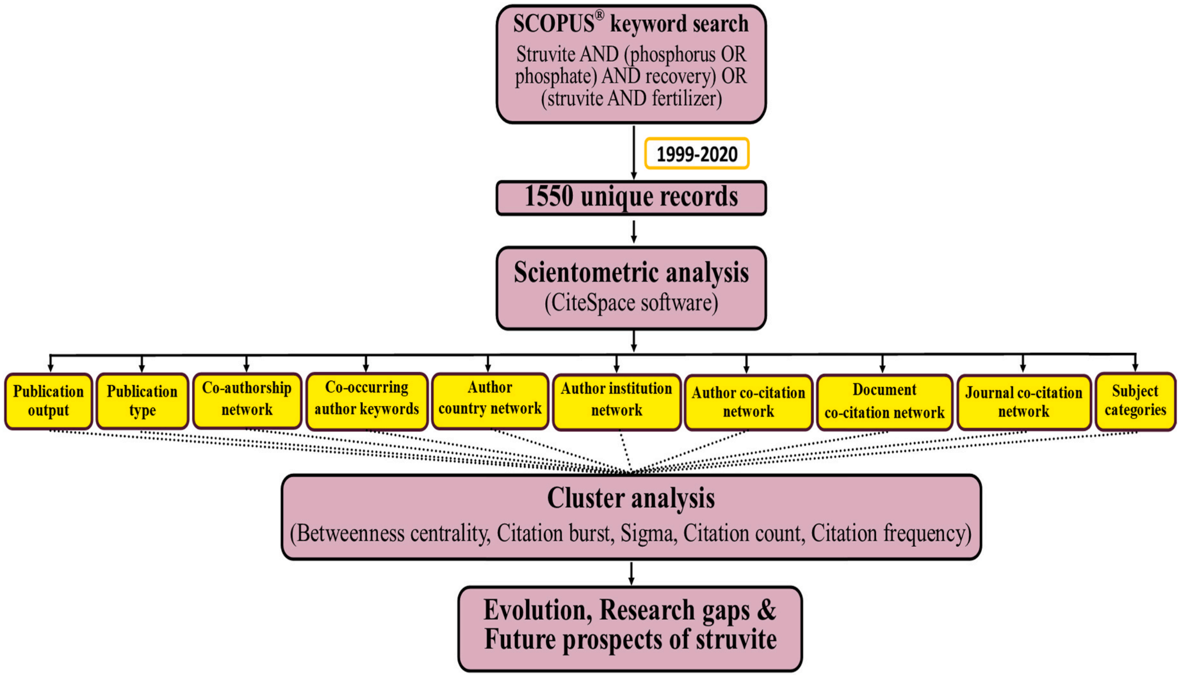

Fig. 1. Flowchart of the methodology of scientometric analysis using CiteSpace 5.7.R2.

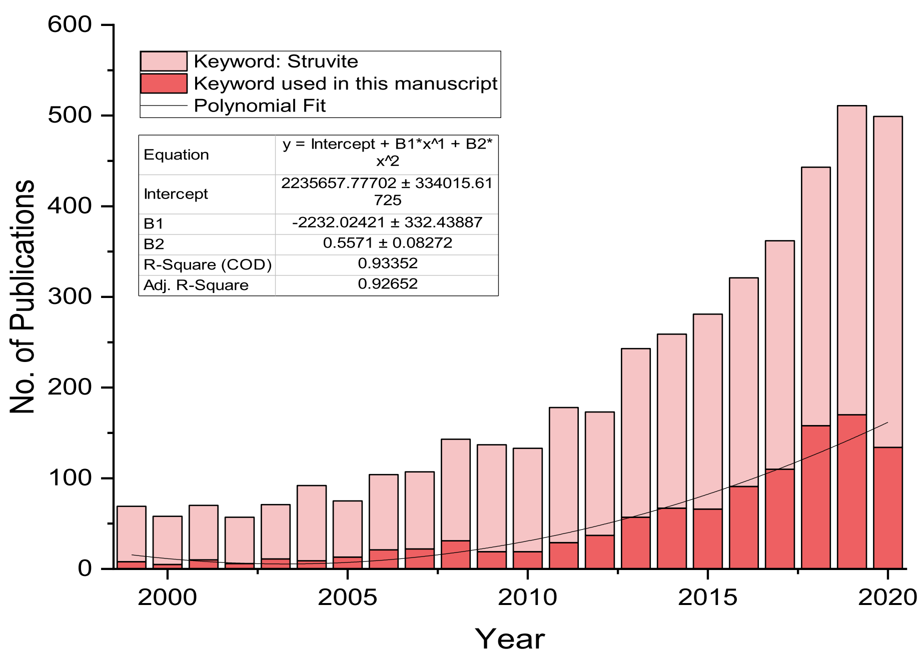

Fig. 2a. Annual number of documents published on struvite research over the years 1999–2020.

denote the variation in studies conducted by authors from several research groups. For instances, M Maurer and Loosdrecht Van's teams are present in distant clusters away from the main network indicating dissimilarity in their research.

Similarly, clusters that are one node away from the main domain differ slightly in their study area. These nodes are called turning points that lead to progression in research. Fig. 3b depicts the authors' timeline view and their active contribution periods and clusters based on their primary research interest. The connecting colored lines reveal the collaboration of authors among and between clusters. Cluster #0 is the largest of all, focussing on struvite crystallization followed by product speciation (cluster #1) and tightening effluent standard (cluster #2). The absence of few clusters is due to insufficient data in them. The top five authors in terms of the number of articles published are DS Mavinic (23 documents), X Wang (21 documents), Y Liu (20 documents), J Li (19 documents), and H Huang (19 documents). The works of DS Mavinic and his colleagues were mostly on thermodynamics (Bhuiyan et al., 2007), chemical kinetics (Rahaman et al., 2008), study of influential parameters that control struvite crystallization (Fattah et al., 2012; Rahaman et al., 2008) and construction, and modeling of pilot-scale struvite reactors like fluidized bed reactor and fluidized bed crystallizer (Iqbal et al., 2008). X Wang's group focussed on food waste composting for struvite formation (Wang et al., 2016). Research groups of Y Liu, J Li, and H Huang studied various aspects of struvite precipitation like

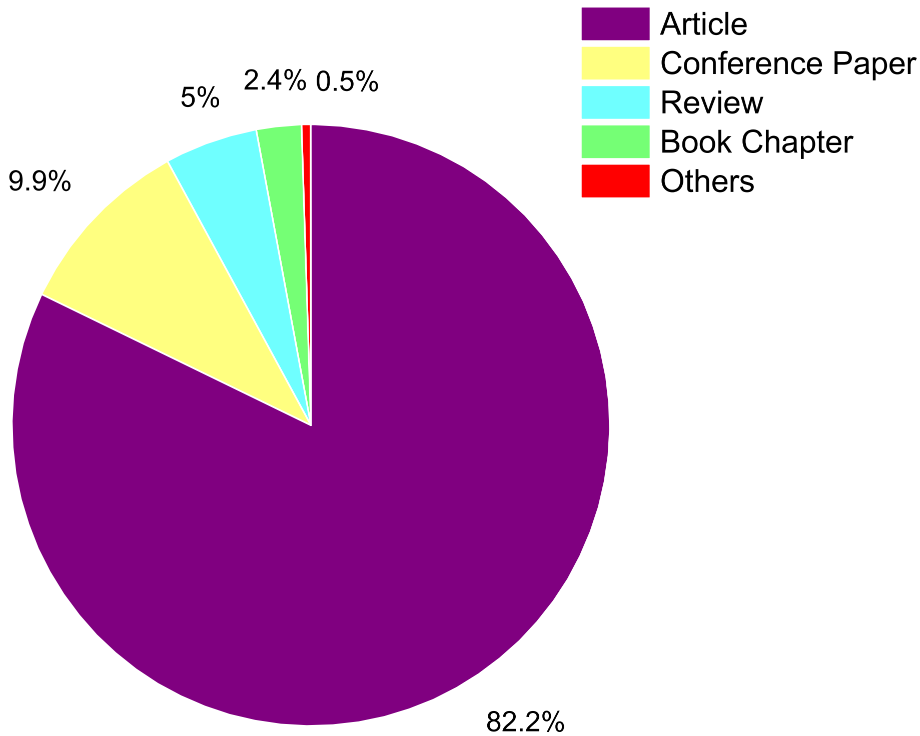

Fig. 2b. Type of documents published on struvite research for fertilizing applications during the period 1999–2020.

ammonia nitrogen and phosphate recovery, presence, and influence of co-existing compounds and heavy metals like potassium, sodium, copper, zinc, and chromium.

3.4. Network of co-authors' countries

Following the number of publications contributed by various countries, top fifteen countries' list is shown in Fig. 4. China is ranked the highest with 296 articles, followed by the USA (206) and Canada (96). These countries have shown remarkable commitment and productivity towards struvite research which can be attributed to the increasing environmental concerns and market demands. The next four countries, Spain (68), Germany (61), Australia (58), and United Kingdom (58), do not have significant differences in their contributions. Most of these countries have made efforts in the collection and processing of wastewater for struvite precipitation. Large reactors have been installed for mass production and commercialization of struvite in various countries. Among the top 15 countries listed, India is the second developing country next to China, where the interest in struvite has just flourished. Agriculture has a significant strategic position in the foundation and economy of these countries. Fig. 4 (inset) represents a cluster network of countries that have collaborated and contributed to struvite research. This visualization further supports and gives a clear idea of the significant publication contribution from countries worldwide. The bigger the size of the represented country's name and node, the greater is the number of articles contributed from the corresponding country. The links between the countries indicate the collaboration between them and provide an overall idea of each country's work aspect.

3.5. Co-occurring author keywords

Keywords or key phrases depict the field topic or research hotspot of a document. The evolution of keywords over time can monitor the progress or development made in a particular area. They also help in the identification of specific articles in our arena of interest. Several words co-appear in various articles. CiteSpace was used to analyze such terms to pick out the most frequent ones based on citation burst in scales of five years, and the following results are revealed (Table 1). 'Wastewater treatment' and 'magnesium ammonium phosphate' are the recurring keywords between the years 1999–2010. The increase in the number of keywords with the strongest citation bursts also shows the increasing concern in the field of struvite research. Between the years 2011–2015, terms like 'hydrolysis', 'molar ratio', 'initial concentration', 'particle size' have occurred with higher strengths. From the overall perspective of wastewater treatment, researchers have carried forward the idea of looking into the actual chemical kinetics for struvite precipitation. Studies on molar ratios for the external addition of magnesium were carried-out in most studies, including other process parameters whose optimization can increase the particle size of struvite.

Further, various magnesium sources as 'magnesium chloride' and 'seawater' were experimented with to find the most suitable and economical one. It has been reported in the literature that among conventional salts used for struvite formation, magnesium chloride is the most effective in terms of yield, and seawater is mentioned as the cheapest non-conventional source for chemical precipitation of struvite (Liu et al., 2011; Crutchik and Garrido, 2011). Simultaneously, few studies were also conducted on the co-precipitation of heavy metals like 'cadmium' and 'chromium' along with struvite (Scordino et al., 2008). From 2013, the field branched out to identify suitable reactor designs for increasing the yield and scaling-up the process (Guadie et al., 2013).

From 2016, the development in struvite research has reached new heights. Scientists focussed on making the process more sustainable by introducing novel techniques like 'microbial fuel cells' and 'microbial electrolysis cells'. These devices employ electrogenic microorganisms to perform multiple functions like wastewater treatment, nutrient recovery in the form of struvite, and generation of electricity by microbial enzyme catalytic metabolism (Nancharaiah et al., 2016; Zamora et al., 2017). The effect of other ions presents in wastewater like 'sodium' on struvite formation was studied, and it was found that beyond a certain concentration, it can alleviate the crystallization process (Huang et al., 2019). In addition, the possibilities of the formation of struvite analogues like Na-Struvite and K-Struvite were explored (Perwitasari et al., 2017).

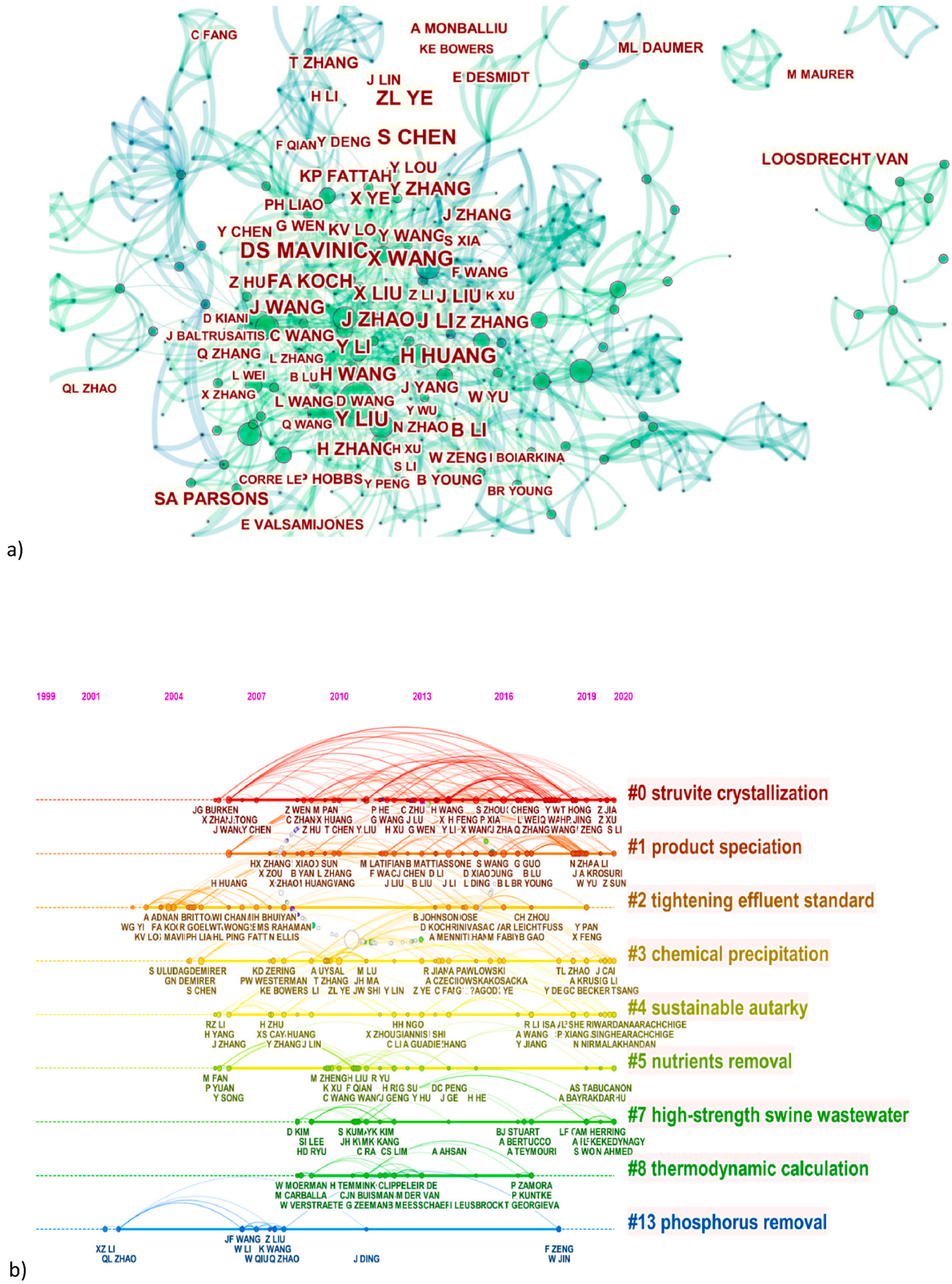

Fig. 3. a) Cluster and b) Timeline view of author contribution towards struvite research (1999–2020).

Electrochemistry was combined with struvite technology by using magnesium 'electrode' instead of chemical precipitation for making the process more efficient, automated and economic (Kim et al., 2018). The research focus was more on the aspects of 'cost-benefit analyses and 'cost-effectiveness'.

3.6. Author co-citation network

Author co-citation network or cited author analysis was performed using CiteSpace, and the results obtained can be interpreted based on CC, CB, sigma, and CF. Table 2 represents the list of the most cited author in struvite research in the order of CF. Le Corre KS and Doyle JD

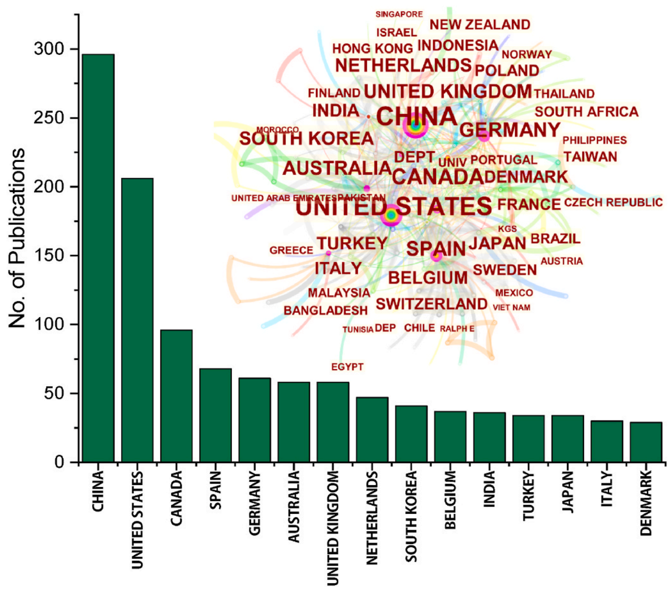

Fig. 4. Top 15 countries worldwide and the schematic network of countries (inset) contributing to struvite research from 1999 to 2020.

from England, and Cordell D from Australia were the most highlighted authors in terms of CF. Concerning CB, Battistoni P, Munch EV, and Driver J have the highest burst strengths of 27.17, 15.37, and 12.55, respectively, indicating the significant attention given to their works. The sigma values remained 1.00 while the centrality was 0.00 for all the cited authors. The nodes have a considerable impact on the network's structural and temporal properties; however, they are not due to insufficient collaboration. Fig. 5 depicts the network of the most cited authors along with clusters. Authors Doyle JD, Battistoni P, Ohlinger KN, Stratful I, Bhuiyan MIH, and De-Bashan LE belong to the strongest cluster #0 (struvite formation), wherein the significant keywords based on their contributions include struvite precipitation, modeling, dynamic simulation, source-separated urine, and continuous-flow struvite crystallizer. Le Corre KS, Huang H, Rahman MM, Nelson NO, Pastor L, and Zhang T come under the second strongest cluster #1 with the contribution in recovery, chemical precipitation, biotransformation, magnesium mineralization, and hydrothermal carbonization for struvite precipitation. Cluster #8 (nutrient flux) and #9 (algal) are situated away from the main domain, differentiating their study aspects from other clusters.

3.7. Document co-citation network

Document co-citation network or cited article analysis was performed using Citespace. The top five articles with the highest number of citations during the period 1999–2020 are (1) Recent advances in removing phosphorus from wastewater and its future use as fertilizer (1997–2003) by De-Bashan and Bashan (2004) (CC = 980); (2) Struvite formation, control and recovery by Parsons & Doyle (2002) (CC = 591); (3) The disappearing nutrient by Gilbert (2009) (CC = 501); (4) Phosphorus recovery from wastewater by struvite crystallization: A review by Le Corre et al. (2007) (CC = 386) and (5) Controlled struvite crystallization for removing phosphorus from anaerobic digester side-streams by Munch and Barr (2001) (CC = 358). Citation burst was performed to identify the articles with high citation strength during the time-period of interest. According to functionalities of CiteSpace 5.7.R2, the references were sorted by strength of the burst as shown in Table 3. 'Struvite formation, control and recovery' by Doyle JD has the highest burst strength of 10.02 with most citation during the last fourteen years. The most cited article by De-Bashan and Bashan (2004) ranks fifteen in the list with a strength of 7.02.

Table 1
Keywords with the strongest citation bursts on struvite research between periods 1999–2020.

Sl. No.	Keywords	Strength	1999 - 2005	Keywords	Strength	2006 - 2010	Keywords	Strength	2011 - 2015	Keywords	Strength	2016 - 2020
1	Recycling	3.32		Model	2.04		Cadmium	1.98		Metabolism	2.28	
2	Water Treatment	2.09		Chemicals Removal	2.36		Molar Ratio	3.07		Bioenergy	2.55	
3	Ammonium Magnesium Phosphate	2.79		Waste Treatment	1.95		Nonhuman	2.58		Cost Benefit Analysis	2.28	
4	Magnesium Ammonium Phosphate	2.08		Water Treatment	2.09		Ammonium Compound	4.47		Microbial Activity	2.91	
5							Ammonia Nitrogen	1.98		Microbial Fuel Cell	2.35	
6							Leaching	2.38		Electrode	2.55	
7							Chromium	1.98		Waste	2.55	
8							Initial Concentration	2		Fuel Cell	3.64	
9							Chemical Composition	2.04		Sodium	2.56	
10							Magnesium Chloride	2.04		Magnesium Phosphate	2.31	
11							Particle Size	2.72		Concentration (Parameters)	2.87	
12							Fluidized Bed Reactor	1.81		Sewage Treatment	2.05	
13							Hydrolysis	3.41		Chromium	1.79	
14							Kinetics	1.81		Sustainable Development	2.83	
15							Seawater	1.81		Cost Effectiveness	2.02	
16										Metal Ion	2.83	
17										Nutrients Recovery	1.82	
18										Oxidation	1.82	

Table 2
List of the top 15 most cited authors on fertilizing application of struvite with respective scientometrics.

Cited author	Country/ territory	Year	Burst	Sigma	Frequency	Cluster ID
Le Corre KS	England	2007	–	1.00	317	1
Doyle JD	England	2004	5.68	1.00	267	0
Cordell D	Australia	2010	–	1.00	224	4
Battistoni P	Italy	2000	27.17	1.00	192	0
Huang H	China	2007	–	1.00	186	1
Ohlinger KN	USA	2002	20.66	1.00	185	0
Ronteltap M	Switzerland	2009	7.49	1.00	177	2
Jaffer Y	England	2001	10.23	1.00	162	6
Stratful I	England	2004	13.04	1.00	150	0
Rahman MM	Malaysia	2014	–	1.00	150	1
Nelson NO	USA	2005	7.96	1.00	144	1
Pastor L	Spain	2010	8.08	1.00	132	1
Bhuiyan MIH	Canada	2008	5.90	1.00	126	0
De-Bashan LE	Mexico	2007	8.04	1.00	125	0
Zhang T	Washington	2011	–	1.00	125	1

(The parameter "year" in this table indicates the specific year in which the citation burst was initiated. Cluster ID represents the cluster number shown in Fig. 5).

3.8. Network of authors' institutions

The node 'institution' was selected in CiteSpace for analyzing the productive contribution of various institutions around the world on phosphate recovery as struvite and utilization as fertilizer from 1999–October 2020 (Table 4). Tongji University from China secured the highest rank with a publication count of 44 documents, followed by The University of British Columbia, Canada, with 38 documents. China seems to be the largest contributor to struvite research. Other institutes from China that serve a significant impact on struvite research are the Chinese Academy of Sciences, Ministry of Education China, University of Chinese Academy of Sciences, Tsinghua University, China Agricultural University, and Yanshan University. Though these conclusions are made based on publication quantity, several countries like Canada, UK, North America, Netherland, and Nepal have commercially installed struvite production plants (discussed in detail in section 4.3).

3.9. Journal co-citation network

Journal publication analysis was performed using the 'cited journal' node in CiteSpace. This represents the number of documents published and citations received by a journal from 1999 to 2020. This scientometric software helps identify journals with a high contribution in published quantity (Table 5) and citation frequency. According to the output concerning the number of articles published, 'Water Science and Technology' ranks the highest with 75 documents. The second-ranked journal is 'Water Research' with 61 publications. 'Bioresource Technology', 'Environmental Technology United Kingdom' and 'Journal of Cleaner Production' are ranked third, fourth and fifth with 46, 45, and 40 published documents, respectively. As a publisher, Elsevier contributes the highest to struvite research.

3.10. Co-occurring subject categories

Subject category analysis helps in classifying the published documents on struvite research based on the particular scientific area. Fig. 6 represents the contribution percentages of various subject categories under struvite crystallization process, characterization, and application. Based on the results, the five most important categories are 'Environmental science' (897 documents), 'Chemical engineering' (236 documents), 'Chemistry' (219 documents), 'Engineering' (218 documents), and 'Energy' (165 documents). Few other categories that have contributed are 'Earth and planetary sciences', 'social sciences' and 'Immunology and microbiology'.

4. Discussion

4.1. Evolution of struvite research

The compound struvite was accidently discovered in 1961 during the production of liquid fertilizer from phosphoric acid. However, it was considered an impurity and left understudied. The value and application of struvite were understood only in the late 90s, and since 1999, the research on struvite took its stage. There has been a tremendous increase in the number of journals published on struvite research, especially on fertilizing applications. Other than this, its presence in kidney stones and pipe blockages has also been widely studied. Owing to the crisis of non-renewable phosphate mineral depletion and eutrophication, the research on struvite has been in the limelight during the last two decades. The research quantum reached its peak in 2019, and many advances have been brought in for the complete recovery of phosphorus

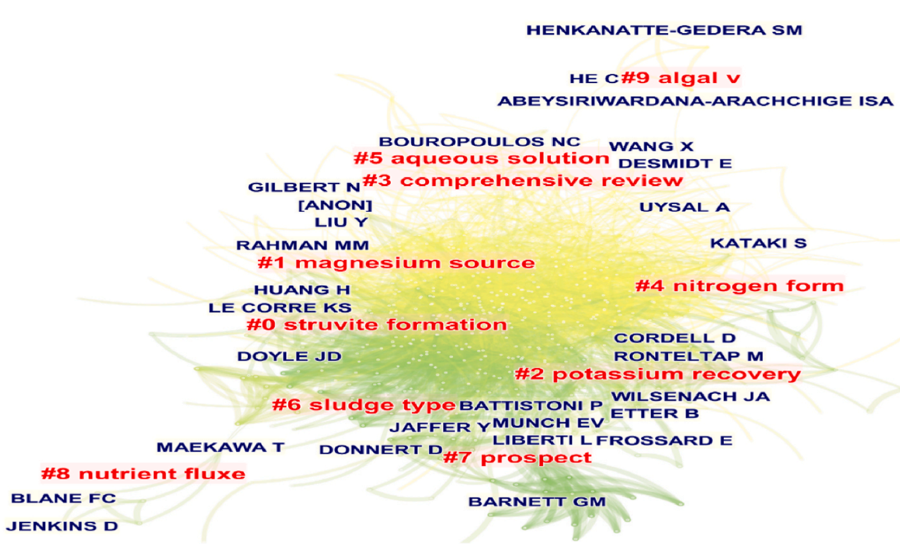

Fig. 5. Cluster view of author co-citation network on struvite research between 1999 and 2020.

from any possible source. This section will discuss the developments in struvite research since its bloom until today based on the evolution of keywords over the years. Fig. 7 depicts the timeline of the revolutionary discoveries made in struvite research.

The interest in struvite research bloomed in 1999, after which the number of articles published every year increased exponentially. Initially, the primary research was focussed on phosphate recovery irrespective of the source. Later, the additional benefit of ammonium recovery further elated the curiosity in struvite extraction. Gaterell et al. (2000) compared and evaluated the economic and environmental aspects of struvite produced from wastewaters with commercial fertilizers available in UK fertilizer markets. He concluded that the high recovery rate is feasible with comparatively simple process configurations, making them satisfy the regional and economic demands. Lind et al. (2000) experimented on ammonia adsorption on zeolite and wollastonite to enhance nutrient recovery from human urine. Though the authors have touched-upon, various aspects of struvite research, only limited articles and support documents were available for consideration of this technology to the next level. Li and Zhao (2002) utilized seawater bittern waste for precipitation of struvite from landfill leachate. Quintana et al. (2004) used a by-product of magnesite mining and MgO production to substitute for convention chemical magnesium sources.

Several pre-treatments were also adapted to enhance the phosphate recovery. An advanced oxidation process involving microwave treatment and hydrogen peroxide was used to improve the phosphorus solubilization liquid dairy manure. This method aided phosphate release up to 85% and augmented struvite recovery (Wong et al., 2006). In this period, the use of seeding materials to improve the size of struvite crystals was established. A separate seeder reactor and a fluidized bed reactor were used to manage struvite crystal growth for proficient phosphate recovery (Shimamura et al., 2007). Another unique study was carried out to test the feasibility of waste lime to perform as a potential cation source for the struvite crystallization process (Ahn and Speece, 2006). Human urine was found to be a likely source for struvite formation, as it comprises phosphate and ammonium in sufficient quantities. In fact, human urine alone contributes to 40–50% of phosphate and 80% of nitrogen to municipal wastewater. This provoked the idea and significance of source separation, and enormous studies on human urine are being conducted.

In the commercialization outlook, researchers worked on the precipitation composition of struvite as the NPK value plays a crucial role in fertilizers' economic status. Studies were conducted in determining the inherent factors (i.e., pH) that affect the composition of struvite. Other than the previously reported wastewater sources, the efficacy of various other sources like dairy cattle manure (Rico et al., 2011), pharmaceutical wastewater (Qiu et al. 2011), frozen fish industry, hog lagoon supernatant (Ackerman and Cicek, 2011), sewage sludge ash, semiconductor wastewater (Ryu et al., 2012a,b) and poultry manure on struvite recovery were explored in this period. The concepts of microbial fuel cells (MFC) and microbial electrolysis cells were introduced from a struvite precipitation perspective (Krishnamoorthy et al., 2021a). Ichihashi and Hirooka (2012) used an air-cathode single MFC chamber to release the influent phosphate from swine wastewater. It was found that the struvite deposits on the surface of the cathode with the recovery of 70–82% recovery from the influent. Similarly, Cusick & Logan (2012) investigated a microbial electrolysis cell (MEC) for the combined production of struvite and hydrogen gas.

Many life cycle (LCA) and techno-economic assessments (TEA) have been performed to compare struvite precipitation from conventional wastewaters and source-separated urine (Bisinella de Faria et al., 2015; Ishii and Boyer, 2015). Algae-based sewage treatment and resource recovery (STaRR) presented the use of mixotrophic algae, Galdieria sulphuraria for simultaneous exclusion nutrients and dissolved organics from primary effluent. This approach was followed by hydrothermal liquefaction to remove algal biomass and subsequent nutrient recovery as struvite. The process yields two by-products, one rich phosphate

Table 3
Top 20 references with strong citation burst on struvite research between 1999 and 2020.

References	Year	Strength	Begin	End	1999 - 2020
Doyle, J. D., & Parsons, S. A. (2002). Struvite formation, control and recovery. *Water research*, *36*(16), 3925-3940.	2002	10.02	2007	2020	
Münch, E. V., & Barr, K. (2001). Controlled struvite crystallisation for removing phosphorus from anaerobic digester sidestreams. *Water research*, *35*(1), 151-159.	2001	9.42	2009	2020	
Suzuki, K., Tanaka, Y., Kuroda, K., Hanajima, D., Fukumoto, Y., Yasuda, T., & Waki, M. (2007). Removal and recovery of phosphorous from swine wastewater by demonstration crystallization reactor and struvite accumulation device. *Bioresource technology*, *98*(8), 1573-1578.	2007	8.96	2011	2020	
Ronteltap, M., Maurer, M., Hausherr, R., & Gujer, W. (2010). Struvite precipitation from urine–influencing factors on particle size. *Water research*, *44*(6), 2038-2046.	2010	8.56	2012	2020	
Ueno, Y., & Fujii, M. (2001). Three years experience of operating and selling recovered struvite from full-scale plant. *Environmental Technology*, *22*(11), 1373-1381.	2001	8.44	2004	2020	
Snoeyink, V. L., & Jenkins, D. (1980). *Water chemistry*.	1980	8.33	2005	2020	
Kataki, S., West, H., Clarke, M., & Baruah, D. C. (2016). Phosphorus recovery as struvite: Recent concerns for use of seed, alternative Mg source, nitrogen conservation and fertilizer potential. *Resources, Conservation and Recycling*, *107*, 142-156.	2016	8.33	2018	2020	
Gaterell, M. R., Gay, R., Wilson, R., Gochin, R. J., & Lester, J. N. (2000). An economic and environmental evaluation of the opportunities for substituting phosphorus recovered from wastewater treatment works in existing UK fertiliser markets. *Environmental Technology*, *21*(9), 1067-1084.	2000	8.26	2007	2020	
Ohlinger, K. N., Young, T. M., & Schroeder, E. D. (1998). Predicting struvite formation in digestion. *Water Research*, *32*(12), 3607-3614.	1998	8.15	2007	2020	

Booker, N. A., Priestley, A. J., & Fraser, I. H. (1999). Struvite formation in wastewater treatment plants: opportunities for nutrient recovery. *Environmental technology*, *20*(7), 777-782.	1999	8.14	2000	2020	
Egle, L., Rechberger, H., Krampe, J., & Zessner, M. (2016). Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies. *Science of the Total Environment*, *571*, 522-542.	2016	7.8	2018	2020	
Tao, W., Fattah, K. P., & Huchzermeier, M. P. (2016). Struvite recovery from anaerobically digested dairy manure: A review of application potential and hindrances. *Journal of environmental management*, *169*, 46-57.	2016	7.73	2017	2020	
Burns, R. T., Moody, L. B., Celen, I., & Buchanan, J. R. (2003). Optimization of phosphorus precipitation from swine manure slurries to enhance recovery. *Water Science and Technology*, *48*(1), 139-146.	2003	7.39	2007	2020	
Adnan, A., Mavinic, D. S., & Koch, F. A. (2003). Pilot-scale study of phosphorus recovery through struvite crystallization examining the process feasibility. *Journal of Environmental Engineering and Science*, *2*(5), 315-324.	2003	7.25	2008	2020	
De-Bashan, L. E., & Bashan, Y. (2004). Recent advances in removing phosphorus from wastewater and its future use as fertilizer (1997–2003). *Water research*, *38*(19), 4222-4246.	2004	7.02	2007	2020	
Durrant, A. E., Scrimshaw, M. D., Stratful, I., & Lester, J. N. (1999). Review of the feasibility of recovering phosphate from wastewater for use as a raw material by the phosphate industry. *Environmental Technology*, *20*(7), 749-758.	1999	6.88	2001	2020	
Talboys, P. J., Heppell, J., Roose, T., Healey, J. R., Jones, D. L., & Withers, P. J. (2016). Struvite: a slow-release fertiliser for sustainable phosphorus management?. *Plant and soil*, *401*(1), 109-123.	2016	6.59	2017	2020	
Zhang, T., Ding, L., Ren, H., & Xiong, X. (2009). Ammonium nitrogen removal from coking wastewater by chemical precipitation recycle technology. *Water research*, *43*(20), 5209-5215.	2009	6.57	2016	2020	
Battistoni, P., Fava, G., Pavan, P., Musacco, A., & Cecchi, F. (1997). Phosphate removal in anaerobic liquors by struvite crystallization without addition of chemicals: preliminary results. *Water research*, *31*(11), 2925-2929.	1997	6.42	2001	2020	
Pastor, L., Mangin, D., Barat, R., & Seco, A. (2008). A pilot-scale study of struvite precipitation in a stirred tank reactor: conditions influencing the process. *Bioresource Technology*, *99*(14), 6285-6291.	2008	6.3	2010	2020	

Table 4
Institution contribution analysis on struvite research from 1999 to 2020.

Ranking	Affiliation	Country/territory	Count
1	Tongji University	China	44
2	The University of British Columbia	Canada	38
3	Chinese Academy of Sciences	China	36
4	Ministry of Education China	China	27
5	University of Chinese Academy of Sciences	China	23
6	Universiteit Gent	Belgium	21
7	Delft University of Technology	Netherland	19
8	Eawag - Swiss Federal Institute of Aquatic Science and Technology	Switzerland	17
9	University of Manitoba	Canada	17
10	Tsinghua University	China	17
11	China Agricultural University	China	16
12	Yanshan University	China	16
13	The University of Queensland	Australia	16
14	Cranfield University	England	15
15	University of Auckland	New Zealand	15

(solid residue) and another rich in ammonium (aqueous phase) that can be converted to fertilizers. Similarly, aerobic microbial granules were cultivated nitrification-denitrification sequencing batch reactor for initial sludge treatment. This process was followed by a change in reactor's operating conditions to enhance phosphorus release into the liquid for recovery in the form of struvite (Abeysiriwardana-Arachchige et al., 2020; Karbakhshravari et al., 2020; Munasinghe-Arachchige et al., 2020). Struvite precipitation was used in association with biogas production, where the pre-treatment of biogas slurry involved ozone oxidation along with the addition of magnesium oxide as catalysts (Zeng et al., 2020).

4.2. Research gaps, emerging trends and the way forward in struvite research

The cluster analysis and use of keywords over the years can provide an overview of the research gaps and emerging trends in a field. In the case of struvite, it can be observed that laboratory experiments and various other accompanying technologies for struvite precipitation have been employed over the years. However, the optimum range of process parameters such as pH, temperature, magnesium dosage, storage conditions, co-presence of ions has to be worked upon for efficient functioning and scale-up. Storage has been shown to improve ureolysis in urine samples and thus decrease chemical cost (Tilley et al., 2008); yet, measures to fasten the hydrolysis process to speed up the precipitation

Table 5
List of top 15 journals that contributed to struvite research from 1999 to 2020.

Ranking	Journal Name	Publisher	Published quantity	Contribution (%)
1	Water Science and Technology	International Water Association	75	6.28
2	Water Research	Elsevier	61	5.10
3	Bioresource Technology	Elsevier	46	3.85
4	Environmental Technology United Kingdom	Taylor & Francis	45	3.76
5	Journal of Cleaner Production	Elsevier	40	3.35
6	Chemosphere	Elsevier	34	2.84
7	Chemical Engineering Journal	Elsevier	30	2.51
8	Environmental Science And Pollution Research	Springer	29	2.42
9	Science of The Total Environment	Elsevier	29	2.42
10	Environmental Science And Technology	American Chemical Society	26	2.17
11	Journal of Environmental Management	Elsevier	24	2.01
12	Desalination And Water Treatment	Desalination publications	21	1.75
13	Journal of Chemical Technology and Biotechnology	Society of Chemical Industry	17	1.42
14	Huanjing Kexue Xuebao Acta Scientiae Circumstantiae	Science Press	15	1.25
15	Journal of Hazardous Materials	Elsevier	15	1.25

have to be initiated. Aspects of preventing ureolysis and thus microbial growth in case of prolonged storage should also be focussed. Only a few reactor designs for pilot scale operations have been explored, and the technical benefits of the infrastructure are scarcely explained. For instance, the reason for the fluidized bed reactor design, which has been widely commercialized, is limited in the literature. Modeling studies with mathematical and chemical equilibrium models for struvite crystal formation and precipitation have been devised extensively. Recently established machine learning, neural network, and artificial intelligence methods can be integrated to better predict phosphorus recovery. Most of the studies on struvite recovery were performed on synthetic wastewater with a composition similar to real-time wastewaters. Experiments on actual wastewater can better understand the real advantages and problems faced while handling them. Besides, attention to segregation of wastewater collection for better resource recovery is required. A mixture of various wastewaters will make the process more intensive due to solid particles and microbial colonies' segregation. The existence of microorganisms in the freshly precipitated struvite is usual and can be overcome by proper drying of crystals. Drying is also an essential aspect of struvite research that needs more deliberation not only because of sterilization but also due to variation in the composition of compounds formed with respect to temperature (Bischel et al., 2016; Schürmann et al., 2012). Considering the adsorption property of struvite and presence of heavy metals and other co-existing ions in wastewater, co-precipitation during crystallization should also be a matter of concern for application as fertilizer in agricultural fields, concerning the risk of integration into the food chain (Chu et al., 2018; Li et al., 2020). For the formation of struvite analogues such as K-struvite and Na-struvite with changes in concentration and operational conditions, the optimum conditions for each formation are not clear. Although K-struvite precipitation is regarded beneficial in terms of plant nutrient requirement, alleviating the effect of sodium on phosphate and potassium recovery has been reported (Huang et al., 2019; Liu et al., 2020; Tao et al., 2020). Struvite is theoretically and experimentally proved an effective fertilizer; however, studies on the application for plant growth are lacking. Owing to the low solubility of struvite in water, the mechanism behind the breakdown and uptake of nutrients from struvite by the plants is still indistinct.

While the application of struvite as fertilizer is widely explored, its ability to adsorb heavy metals and antibiotic resistance genes from the

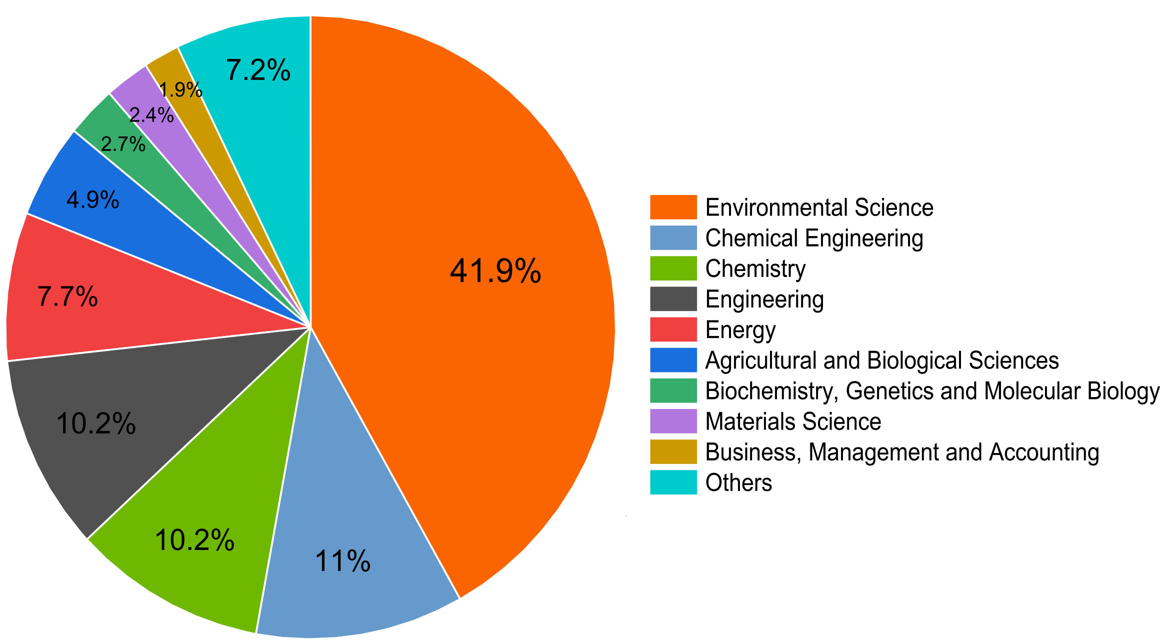

Fig. 6. Contribution of subject categories to struvite research.

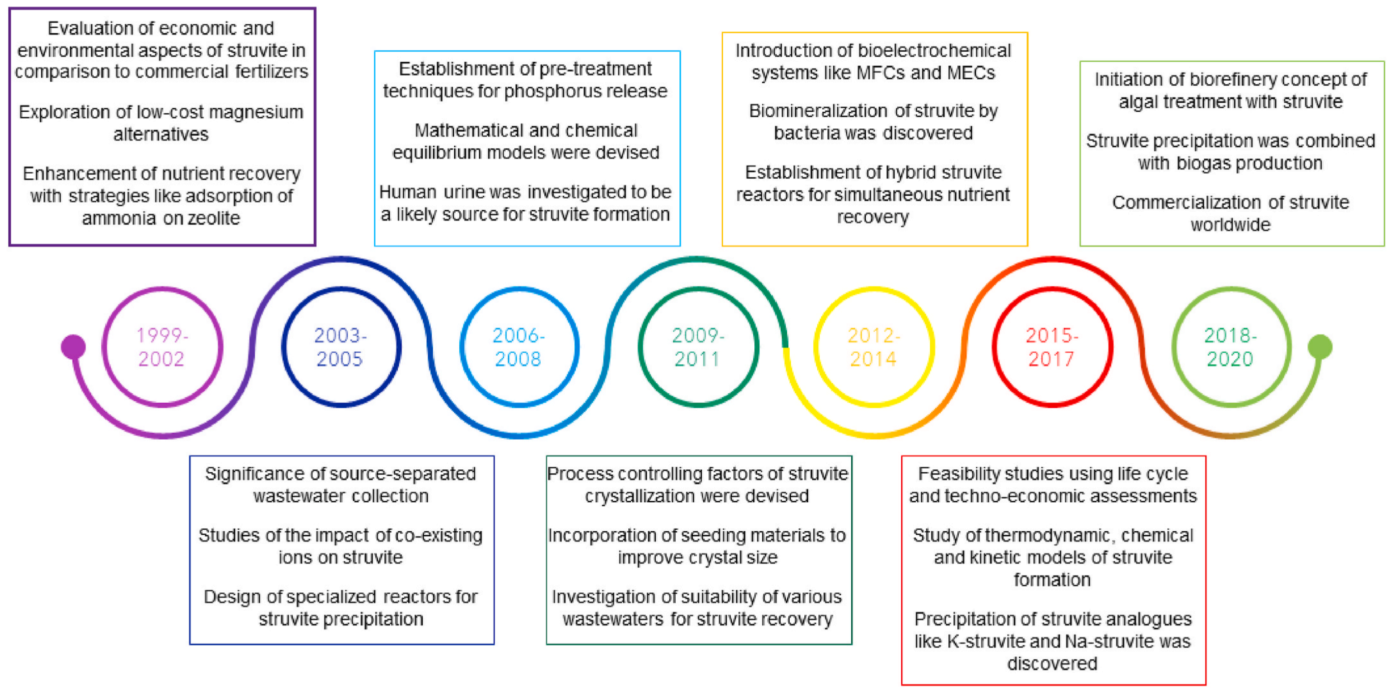

Fig. 7. Timeline view of the evolution of struvite research from 1999 to 2020.

soil is gaining scope in recent years. Moragaspitiya et al. (2020) examined the adsorption efficiency of struvite for copper and zinc from contaminated bio-retention soil. Li et al. (2020) used magnesium hydroxide modified biochar, a struvite supported-biochar composite, for recovering phosphate and ammonium from pig slurry. This composite was used to immobilize copper and antibiotic-resistant genes such as tetT, tetX, tetW, tetG, sulI, sulII, ermB, and intlI from long-term manured soil. Similarly, tetracycline adsorption on struvite crystal was detected while precipitating it from wastewater. Arslanoglu (2019) examined the co-adsorption of Cu(II) and tetracycline onto struvite-loaded zeolite. In another study, struvite palygorskite precipitated from nutrient-rich wastewater with MgO-modified palygorskite was used for copper remediation from contaminated soil (Wang et al., 2020). The use of struvite as a fire-retardant barrier on the flammability of wooden plates and the cotton fabric was investigated by Yetilmezsoy et al. (2020).

Modified biochar for struvite precipitation is emerging due to the additional benefit of seeding. In this view, magnesium-laden biochar produced from wood waste was utilized to recover phosphate and potassium as K-struvite (Liu et al. 2020). It is reported that biochar produced from fermentation residues has phosphate forms more readily available to plants than struvite. Hence the association of biochar with struvite will increase its nutrient value as fertilizer. Some of the other components reported to enhance the struvite crystal size and recovery are steel powder and struvite itself (Addagada, 2020). The struvite fines that get precipitation because of spontaneous precipitation are being used to enhance phosphate recovery. A novel study was performed by Youzhi et al. (2020), where struvite was combined with gelatin, chitosan, and fulvic acid through emulsion cross-linking to produce soil conditioner microspheres. These sustainable macromolecules possess benefits like water-retention capacity, heavy metal settling, and crop growth promotion. The introduction of pre-treatment methods to enhance phosphorus removal plays a significant role in the developing the field. The interest in the biorefinery aspect, such as integration of algal culturing with struvite precipitation also increases. Future research on the type of wastewater and its combination that is economically suitable is recommended to improve understanding economics. More focus on the research cost analysis is required. Source-separated wastewaters have recently been under focus for beneficial aspects of storage, treatment, and phosphate recovery. Experiments on precipitating analogues of struvite such as K-struvite and Na-struvite assessing their potential as fertilizers are being carried out in recent years (Perwitasari et al., 2017). Various hybrid systems that can improve struvite recovery are being reported in literature (discussed in earlier sections). For example, combining ammonia stripping along with struvite crystallization and other means to avoid ammonia volatilization are being constructed (Folino et al., 2020). Electrochemical struvite precipitation has come into picture due to economic benefits of using magnesium electrodes instead of cost-intensive salts. Further work on microbial fuel cells and microbial electrolysis cells for struvite precipitation is demanding, considering their additional welfares like electricity generation.

4.3. *Commercialization of struvite*

Increase in interest in the field of struvite and introduction of novel technologies lead to commercialization of struvite in various parts of the world. In 2006, a biological nutrient removal process, BCFS (Biological/Chemical Phosphorus and Nitrogen removal), was patented by Hao and van Loosdrecht (2006) for struvite precipitation from anaerobic supernatant. The model was optimized entirely and calibrated with annual production (recovery) of $3.5gN_{tot}/m^3$, $0.5gNH_4\text{-}N/m^3$, and $0.15gP/m^3$. STUN (STruvite from Urine in Nepal) was launched in 2007 for struvite recovery from human urine collected from urine-diversion dry toilets near Kathmandu valley. A 50-L polypropylene hand-powered reactor was installed in the Siddhipur district to produce 327 Kg struvite every year (Etter et al., 2011). Following this, many installations were established for the mass production of marketable struvite. One of the renowned technologies includes Ostara Nutrient Recovery Technologies Inc., which is based in Vancouver, Canada. It has currently established 22 commercial installations worldwide. Ostara's proprietaries Pearl® and WASSTRIP® (Waste Activated Sludge Stripping To Recover Internal Phosphorus) technologies focus on recovering nutrients from municipal, industrial and agricultural waste streams and thus close the phosphorus loop. Pearl® process is the core technology for the production of market-ready struvite in the brand name of Crystal Green. The WASSTRIP® process was launched full-scale with struvite recovery exceeding 1,000,000 pounds. Four reactor models have been commercialized, namely Pearl® 500, Pearl® 2K, Pearl® 10K, and Pearl Fx (Prasad and Schauer, 2012) (https://ostara.com/nutrient-management-solutions/). Another such technology is the PHOSPAQ™ process developed by Paques for possible struvite recovery from industrial effluents, and municipal sludge reject liquors. Continuously aerated reactors for sustainable struvite recovery were installed in Netherlands and UK. This technology was combined with ANAMMOX® (ANaerobic AMMonium OXidation) for robust ammonia removal. The infrastructure is reported to process approximately 60–1100 kg P/day with more than 80–90% recovery efficiency (Paques, 2017; Wilsenach and Van Loosdrecht, 2003). Unitika Ltd. in Japan established the Phosnix© process for struvite crystallization from digester wastewater of sludge in a fluidized bed reactor. From a fertilizer point of view, the struvite crystals are mixed with potassium and sold as 20 Kg bags for 100–200 €, with an estimated price of 210 €/tonne (Crutchik et al., 2017). Based on this technology, a pilot-scale air agitated column reactor with 143 L capacity was developed by Münch and Barr, (2001) in Australia. AirPrex™ is a stirred tank struvite crystallization reactor installed in Netherlands and Germany. This set-up is focuses on stripping out CO_2 for the elevation of pH and facilitating struvite recovery from anaerobic digester wastewater. The start-up was initiated in 2009 at Berlin-Wassmannsdorf and MG-Neuwerk wastewater treatment plants and is aimed at a production of 5000 lbs and 3000 lbs of struvite every day, respectively (Liberti et al., 2001). A similar technology, NuReSeys (Nutrient Recycle Systems), is based in North America and sold under license through Schwing Bioset. The CSTR process involves two reactor units with air-stripping (200 m^3) and crystallization (125 m^3) features for struvite recovery from agro-waste (https://www.waterrf.org/news/nuresys/). Multiform™ recovery systems marketed by Multiform Harvest Inc. also use fluidized bed reactors for nutrient recovery in the form of struvite (http://www.multiformharvest.com/). The ANPHOS® technology developed by Colsen for struvite formation comprises of two process steps; stripping and reaction. This is a batch process with combined CO_2 stripping to increase the pH of the wastewater. The overall struvite production is estimated to be 2500 tonnes/year (https://www.colsen.nl/en/services/p-recovery-struvite). The Seaborne process is aimed at the treatment of sewage sludge for the recovery of struvite. PFI Consulting Engineers monitored the processing infrastructure in cooperation with the Institute of Sanitary and Environmental Engineering at the Technical University of Braunschweig and the Institute of Waste Quality and Waste Management at the University of Hanover. It involves a series of processes such as initial remobilization of nutrients and heavy metals from sludge by decreasing the pH. This step is followed by removing solids using centrifugation and filtration systems, and heavy metals using digester has rich in hydrogen sulphide. Later, struvite can be precipitated by the addition of magnesium oxide and sodium hydroxide (Muller et al., 2007). The above-discussed installations are widely established worldwide; while many such reactors, and technologies are under research, their commercialization is under the pipeline.

5. Conclusion

Struvite is an emerging, cost-effective, and potential alternative to commercially available phosphate fertilizers. These benefits of struvite such as multielement (consists of phosphate, ammonium and magnesium) and cleaner wastewater agent have accelerated its research interest over the years, and the field has reached relative maturity. Some of the key aspects of struvite research including emerging trends, gaps and future prospects are detailed below.

➢ Evolution
- Over the years, research on struvite crystallization has evolved from merely the precipitation of struvite to combination of multiple technologies for improved nutrient recovery.
- Though the technology was initially considered only for phosphate recovery, the benefits of ammonium/ammonia recovery enhanced the curiosity and usage.
- The magnesium sources utilized for struvite crystallization varied from common magnesium salts to cheap alternatives such as bittern, wood ash etc. and magnesium electrodes.
- Struvite was recovered from several wastewater sources, among which source-separated human urine was found to be a better medium due to its high concentration of phosphate and nitrogen.

➢ Research gaps
- Almost 40% of the ammonium is lost during the process of struvite crystallization which greatly affects the struvite yield. This issue needs to be addressed by either reducing the ammonium conversion to ammonia or setting up a separate unit process for recovery.
- Some of the significant research gaps include lack of knowledge on the extent of nutrient available from struvite for plant growth and the nutrient uptake mechanism by plants is still unclear.
- Drying aspects of struvite such as temperature, time and mode, for sterilization and maintaining the molecular integrity of struvite should be focussed.
- Wastewater pre-treatment techniques such as ozone oxidation, thermal hydrolysis, and freeze microwaving etc. to enhance the phosphorus accessibility for struvite formation can be focussed for future research.

➢ Future perspectives
- Use of biochar as a seeding material can be very effective in not only improving the struvite crystal size but also to enhance the nutrient value and slow-release properties of the fertilizer.
- Incorporation of biorefinery techniques along with struvite production are also emerging in recent years.
- Encouraged use of actual wastewaters than synthetic alternatives will help gain better insights on the operational conditions and challenges, for pilot-scale functioning in real-time scenarios.
- Electrochemical method of struvite precipitation is emerging with emphasis on MECs and MFCs. These processes reduce the chemical cost required to enhance the alkalinity of the medium.

These visions can help develop the field for enhanced struvite recovery, thus closing the phosphorus loop for the establishment of the circular economy.

Supplementary material

The e-supplementary data to this article can be found online at https://data.mendeley.com/datasets/fxws9zf8ch/1.

CRediT authorship contribution statement

Krishnamoorthy Nageshwari: Conceptualization, Data curation, Methodology, Software, Writing – original draft. **Paramasivan Balasubramanian:** Supervision, Visualization, Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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