

Review Paper

Phosphorus recovery by struvite precipitation: a review of the impact of calcium on struvite quality

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ABSTRACT

Precipitation of phosphorus (P) as a struvite product from wastewater and local magnesium (Mg) sources is considered as a high economical prudent venture, as it has shown to bring down the cost of producing the product. However, there is a significant concentration of calcium (Ca) in these Mg and most wastewater sources. The presence of Ca in wastewater and Mg sources during struvite precipitation has been shown to negatively affect the quality of the struvite produced. The low struvite quality greatly impedes its use as a fertiliser given the economic value of the product as an alternative P fertiliser. This review paper provides an understanding of how the presence of Ca affects the purity, crystal size, and morphology of the struvite. Different methods that have been used to mitigate the effect of Ca on struvite quality have been reviewed. The factors that affect the recovery of P and the percentage recoveries of P by different Mg sources have also been reviewed. This paper serves as a basis for further research where the possibility of removing Ca from wastewater and Mg sources is explored. When Ca is removed before struvite precipitation is carried out, the quality of the product will be greatly improved.

Key words: calcium, magnesium sources, precipitation, quality, struvite

HIGHLIGHTS

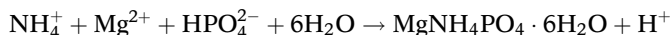
- Trend analysis of impact of Ca on struvite quality has been done.
- All methods for the mitigation of the negative impact of Ca have been reviewed.
- Nutrient removal efficiencies of Mg sources have been compared.
- Molar ratios that affect struvite quality have been identified.
- Research gap for improving struvite quality has been identified.

1. INTRODUCTION

The presence of Ca²⁺ during struvite precipitation has been shown to negatively affect characteristics of the struvite produced (Le *et al.* 2005, Li *et al.* 2016; Liu & Wang 2019; Moragaspiya *et al.* 2019; Bayuseno & Schmahl 2020; Hutnik *et al.* 2020). Precipitating struvite at high Ca concentration produces undesired amorphous product and reduces the proportion of P in the struvite (Desmidt *et al.* 2013; Li *et al.* 2016). This can be attributed to the fact that when the ratio of Ca/Mg is high, the reaction between P and nitrogen (N) reduced (Li *et al.* 2016). The wastewater, which is used (such as swine waste, cattle waste, and faecal sludge effluent) for struvite precipitation, contains some high concentration of Ca. Li *et al.* (2016) reported CO₃²⁻, SO₄²⁻, Ca²⁺, Al³⁺, Zn²⁺, and Cu²⁺ as some of the common ions found in wastewater streams with calcium present at high concentrations. This can be confirmed by Munir *et al.* (2017) in a study where concentrations of PO₄³⁻, Ca²⁺, Cu²⁺, and Zn²⁺ in faecal sludge were determined. They reported concentrations as 31.0, 90.0, 2.5, and 3.4 ppm, respectively. The effluent after undergoing hydrothermal treatment contained 0–90, 30–37, 11–50, and 15–20% of PO₄³⁻, Ca²⁺, Cu²⁺, and Zn²⁺, respectively.

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The precipitation of struvite requires the chemical addition of magnesium (Mg) in a non-spontaneous reaction to form magnesium ammonium phosphate ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) (Barbosa *et al.* 2016).



The commonly used Mg sources used in the struvite reaction in their solution form are MgCO_3 , MgSO_4 , MgO , $\text{Mg}(\text{OH})_2$, and MgCl_2 . The alkaline nature of MgCO_3 , MgO , and $\text{Mg}(\text{OH})_2$ helps by increasing the pH during the precipitation reaction. The struvite precipitation produces H^+ , which decreases the pH, and so requires periodic dosing of NaOH to increase the pH. However, MgSO_4 and MgCl_2 are widely used for phosphorus recovery due to their greater solubility because of their reduced reaction time (Wu & Bishop 2004). Nevertheless, the use of these external Mg sources increases the cost of producing struvite and discourages the production of struvite as a fertiliser. Barbosa *et al.* (2016) reported that the cost of operation for the crystallisation of struvite mainly arises from the cost of reagent, power, and sometimes transportation. An increase in 75% cost has been reported due to the addition of magnesium (Peng *et al.* 2018), and this has hampered the application of struvite as a fertiliser due to the high operational cost (Wang *et al.* 2018). Research has shown that the addition of low-cost magnesium sources can significantly reduce the cost of producing struvite between 18 and 81% (Huang *et al.* 2011; Lahav *et al.* 2013 as cited by Wang *et al.* 2018).

Some natural Mg sources, which have shown potential to precipitate struvite, are wood ash (Sakthivel *et al.* 2012; Huang *et al.* 2017), brucite (Zhang *et al.* 2009; Huang *et al.* 2011; Hövelmann & Putnis 2016), dolomite (Roques *et al.* 1991; Holmberg *et al.* 2000; Chen *et al.* 2017), and bittern, brine, or seawater (Li & Zhao 2002; Ye *et al.* 2011; Lahav *et al.* 2013; Liu *et al.* 2013; Tran *et al.* 2016; Huang *et al.* 2017). These natural sources contain a significant amount of calcium. This review paper discusses the impact of Ca on struvite quality in P recovery, and the methods used for reducing the impact to date has been reviewed to enable the use of an effective method in future studies.

2. OVERVIEW OF RESEARCH

In the past 29 years, there has not been a clear pattern (Figure 1) in terms of published work in studies on the effect of Ca on struvite quality until recently where publication in this area has increased. A total of 60 non-medical publications have been reviewed in the Scopus database. This paper provides a review of the influence of Ca on struvite quality specifically on purity, size, and morphology of the precipitate. In addition, factors that have been used to mitigate the effect of Ca have also been reviewed. In this review, the nutrient (P and N) removal efficiencies of different Mg sources have also been considered.

Figure 1 shows a general view of non-medical research on how Ca influences struvite quality since 1991. The number of publications has been very low with an increase from 7 in 2019 to 11 as of October 2020. This can be corroborated by Li *et al.* (2019a, 2019b) in their review paper where they reported low publication on struvite quality research which is needed for industrial application. However, research activities in struvite precipitation have rather seen a gradual increase since 2010.

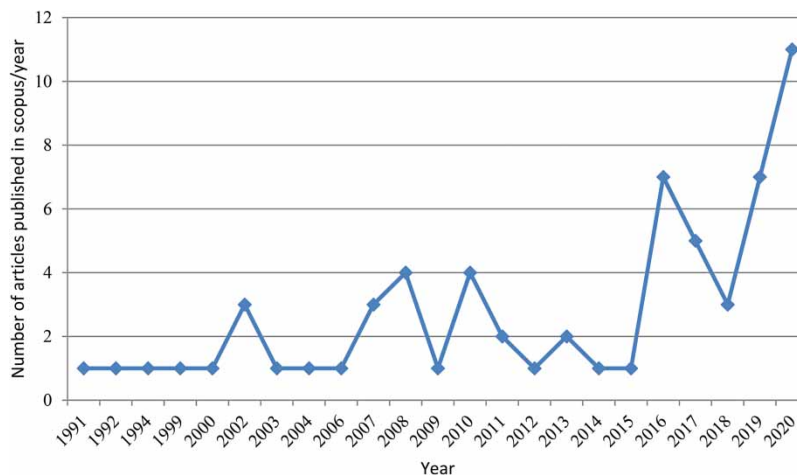


Figure 1 | Non-medical publications on the influence of Ca on struvite quality.

The direction of research (Table 1) has been how Ca concentration in solution influences the struvite purity, crystal size, and morphology and the methods used to mitigate the negative impacts it has on struvite products. Published paper by wastewater type (Figure 2) shows that majority of the wastewater source used is synthetic. The synthetic wastewater enables the researcher to manipulate the concentrations of Ca, Mg, NH₄-N, and PO₃-P in solution and observe how the different molar ratios affect struvite size, purity, and morphology. The different concentrations are also manipulated to enable a researcher to observe how the negative impact of Ca on struvite quality can be mitigated.

Currently, China is leading the research, in terms of published papers, on the influence of Ca on the quality of struvite as can be seen in Figure 3.

3. EFFECT OF CALCIUM ON STRUVITE QUALITY

3.1. Struvite purity

The purity of the struvite product is determined by the percentage mass of the pure struvite (MgNH₄PO₄·6H₂O) in the total precipitate. The higher the struvite purity, the greater its effectiveness as a fertiliser.

Different methods have been used to determine struvite purity in the literature by analysing the concentration of NH₄-N in the precipitate formed (Hao *et al.* 2013; Sun *et al.* 2020). NH₄⁺ is removed from the solution only during the formation of struvite. It is not involved in any reaction, which competes for PO₄³⁻; therefore, when a certain mass of the precipitate is first dissolved in HCl and then diluted with water, the purity of the struvite can be calculated by using the following equation:

$$\% \text{ purity of struvite} = \frac{n(\text{NH}_4 - \text{N}) \cdot (\text{MW}_{\text{struvite}})}{\text{mass of dissolved ppt}} \times 100$$

Table 1 | Presenting the influence of Ca on struvite purity and size from various wastewater sources and according to various investigators

Wastewater type	Mg source	Mg/Ca ratio	Struvite purity (%)	Crystal size (µm)	Key findings	References
Synthetic	MgCl ₂ ·6H ₂ O	1:0	95.51	–	XRD result revealed that up to 31.4% amorphous material was produced.	Moragaspiya <i>et al.</i> (2019)
Synthetic	MgCl ₂ ·6H ₂ O	1:1	73.31	–		
Synthetic	MgCl ₂ ·6H ₂ O	1:2	81.06	–		
Fertiliser industry	MgCl ₂ ·6H ₂ O	0.04% Ca	–	36.8	Crystallisation reaction of struvite was affected by the presence of Ca ions. The presence of Ca in the processing system resulted in the co-formation of amorphous calcium phosphates.	Hutnik <i>et al.</i> (2019)
Cattle manure	MgCl ₂ ·6H ₂ O	0.12% Ca	–	40.2		
Synthetic	MgCl ₂ ·6H ₂ O	0.15% Ca	–	24.5		
Urine	Seawater	4.7:1	92.8	–	The presence of Ca in the Mg sources can compromise struvite purity. It was found that the higher the Mg/Ca ratio in the Mg source, the higher the struvite purity could be obtained.	Liu <i>et al.</i> (2013)
Urine	Brine	10.4:1	96.6	–		
Urine	MgCl ₂	1:0	99.9	–		
Swine	MgCl ₂	1:1	38	–	Calcium is the major competing ion in struvite formation, and struvite purity can be greatly decreased when the Mg/Ca ratio is less than 1.	Wang <i>et al.</i> (2005)
Swine	MgCl ₂	2:0.5	85	–		
Swine	MgCl ₂	2:1	62	–		
Synthetic	MgCl ₂ ·6H ₂ O	1:0	–	13.4–15.1	An increase in Ca concentration during struvite precipitation reduces the crystal size and impedes the struvite growth and leads to the production of amorphous substances instead of crystalline struvite.	Le <i>et al.</i> (2005)
Synthetic	MgCl ₂ ·6H ₂ O	1:1	–	3.1		
Synthetic	MgCl ₂ ·6H ₂ O	1:2	–	2.7		
Synthetic	MgCl ₂ ·6H ₂ O	2:1	–	4.5		
WWTP effluent	MgCl ₂ ·6H ₂ O	1:7	–	14		

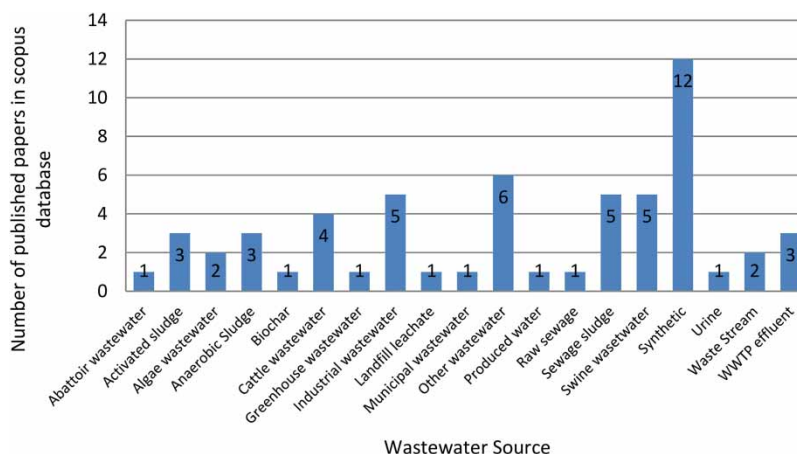


Figure 2 | Non-medical publications on wastewater sources on the influence of Ca on struvite quality.

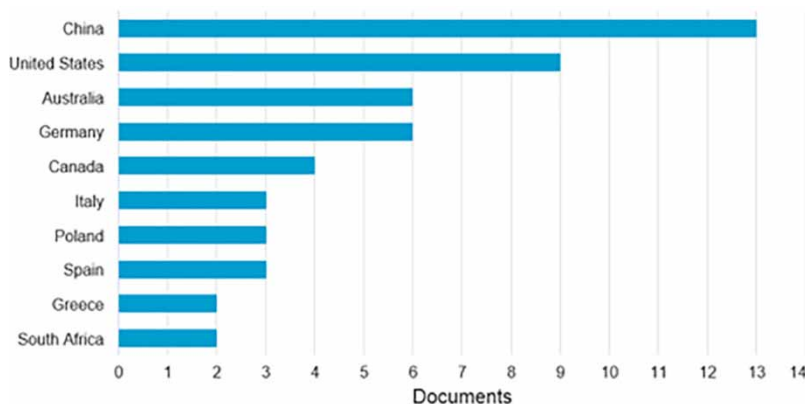


Figure 3 | Non-medical publications on the influence of Ca on struvite quality by country.

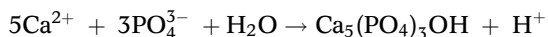
where $n(\text{NH}_4 - \text{N})$ is the number of moles of dissolved struvite, which is determined by the titrimetric method, and $\text{MW}_{\text{struvite}}$ is the molecular weight of the struvite (Clesceri *et al.* 1999).

Also, the quantitative X-ray diffraction (QXRD) technique has been used to determine the purity of the precipitated struvite. Lu *et al.* (2016) used QXRD to measure elemental concentrations of N, Mg, and P in the precipitate formed. This elemental information from QXRD is compared with elemental concentrations of N, Mg, and P using ICP. The concentration of N obtained from QXRD and ICP was very consistent and it was concluded that the QXRD technique is an effective method to determine $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ content in struvite precipitate. The elemental analysis showed that N in the precipitates produced was primarily from the struvite phase, while Mg and P in the recovered precipitates were from both crystalline (i.e. struvite) and amorphous phases.

Furthermore, by comparing the % mass of Mg, $\text{NH}_4\text{-N}$, and $\text{PO}_4\text{-P}$ in struvite precipitate with theoretical values of Mg, $\text{NH}_4\text{-N}$, and $\text{PO}_4\text{-P}$ in pure struvite, the purity of the struvite can be estimated. The % mass of Mg, $\text{NH}_4\text{-N}$, and $\text{PO}_4\text{-P}$ in pure struvite is 9.9, 5.7, and 12.6, respectively. The % composition of impurities (Ca, Fe, and CO_3^{2-}) in the supernatant can then be measured to ascertain how much of the impurities remain in the precipitate (Huang *et al.* 2006; Kemacheevakul *et al.* 2014).

In addition, energy dispersive spectrometry (EDS) has been used to identify the elemental composition of precipitates to measure the purity of struvite (Le *et al.* 2005). For samples with 0% Ca, the graph showed Mg, P, and O as the highest peaks. This is expected because these are the main elements in struvite in terms of percentage mass. At the Mg/Ca ratio of

1:1 and above, EDS spectrum reveals the formation of amorphous calcium phosphate compounds covering the struvite crystals.



3.2. Crystal size

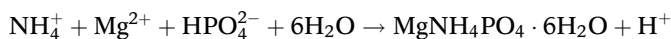
The size attained by struvite crystal during product precipitation depends on a two-step process: nucleation and crystal growth. The growth of the crystal is affected by a combination of several factors such as the pH (Matynia *et al.* 2006), supersaturation, mixing turbulence (Matynia *et al.* 2006), and presence of foreign ions (Le *et al.* 2005; Liu & Wang 2019; Moragaspiya *et al.* 2019; Hutnik *et al.* 2020). Le *et al.* (2005) found that at higher concentrations of Ca (with regard to Mg) in the solution, the mean size of the struvite is decreased. In their experiment to determine the impact of Ca on struvite size, they found that at the Mg/Ca ratio of 1:1 and above, the struvite formed was restricted and crystals were further inhibited by the production of amorphous calcium phosphate. Reaction media without the presence of Ca showed the highest percentage mass of struvite elements (Mg, P, and O) signifying the purity of the element (Le *et al.* 2005). This has been confirmed in a recent study by Moragaspiya *et al.* (2019) that the absence of Ca in media generally resulted in the increase of crystal size with increasing NH_4^+ concentration. Jones (2002) attributed the slow growth rate of crystals by Ca in solution to the blocking off sites where crystals could form, resulting in the inhibition in the growth of struvite crystals. The size of the struvite crystal is significant to ease the recovery of the precipitate. This is because the finer struvite crystals, the more easily they can be discharged along with the effluent, resulting in a loss of crystals. Larger particle size has more benefits than smaller particle size; the larger the particle size, the easier it can be separated, the higher the P recovery efficiency, the lower their solubility, and they are less prone to be washed out (Ronteltap *et al.* 2010). This can be confirmed by Wei *et al.* (2018) in their study on phosphorus recovery from the urine of pregnant women. In that study, 94% of phosphorus was precipitated as struvite, but only 55% was removed from solution.

Rahman *et al.* (2011) showed that the addition of seed materials did not significantly affect the crystal size of the struvite formed. Nevertheless, Liu *et al.* (2014) pointed out that adding seed materials significantly affect the crystal size of the struvite formed with the crystal size increasing from 33.7 to 57.0 μm with multi-stage addition of zeolite, whereas it was 44.7 μm with one-stage addition of zeolite. Therefore, the multi-stage addition of zeolite gave the highest effect on crystal growth. In other words, seed materials should be added periodically during a continuously running process.

3.3. Morphology

A scanning electron microscope (SEM) has been used to examine the images of the morphology of struvite precipitates. Tansel & Monje (2018) has reported the presence of impurities, other ions, and changes in pH as factors that can change crystal growth patterns which will result in irregularities in crystal morphology. The shape of struvite products is rod-like in the absence (Figures 5(a), 6(a) and 7(a)) of Ca (Le *et al.* 2005; Moragaspiya *et al.* 2019). It has been described as needle-like (Figure 4(c)) also in the absence of Ca (Le *et al.* 2007; Doino *et al.* 2011; Muster *et al.* 2013; Muryanto *et al.* 2017). In experiments where Ca ion is present at different Mg/Ca ratios, the morphology has been described as arrow-head (Figure 4(d)) (Zhao *et al.* 2019), prismatic (Bayuseno & Schmahl 2020), pyramidal, star, rectangular platelet, elongated platelet, X-shape (Figure 4(b)), or coffin-lid shape (Figure 4(a)) (Prywer & Torzewska 2012).

As the Mg/Ca decreases, the needle-like shape of the struvite associated at the Mg/Ca ratio of 1:0 begins to become shorter (Figure 5(b)), irregular (Figures 5(b) and 7(b)), and thicker (Figures 6 and 7(c)) with increasing Ca concentration. This has been attributed to the interference of Ca in the struvite formation, where Ca reacts with phosphates to form undesirable calcium phosphates (Le *et al.* 2009).



This was supported by Moragaspiya *et al.* (2019) in a recent study on the impact of Ca on struvite crystallisation. Liu & Wang (2019) found that at the Mg/Ca ratio of 1:1 and above, amorphous calcium phosphate compounds precipitate and cover the struvite crystals. Abbona & Franchini-Angela (1990) have explained that due to the lower solubility of calcium phosphates, it nucleates more easily and as a result precipitates faster and easier than magnesium phosphates. At the Mg/Ca ratio of 1:1 and above, energy dispersive spectroscopy (EDS) mapping reveals the formation of an amorphous Ca layer on the

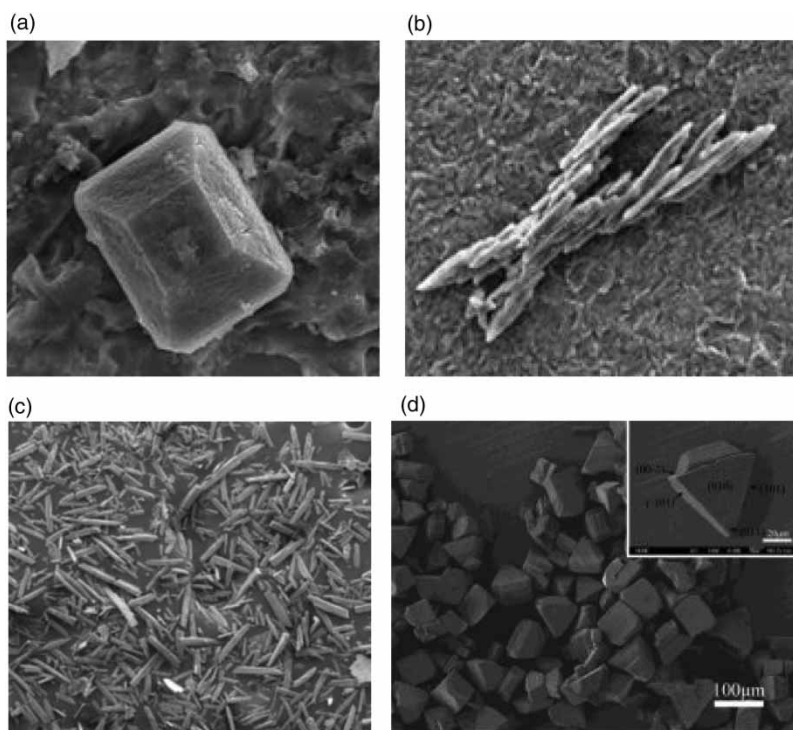


Figure 4 | SEM photograph of struvite: (a) coffin-lid, (b) X-shaped (Prywer & Torzewska 2012), (c) needle-like (Muryanto *et al.* 2017), and (d) arrow-head (Zhao *et al.* 2019).

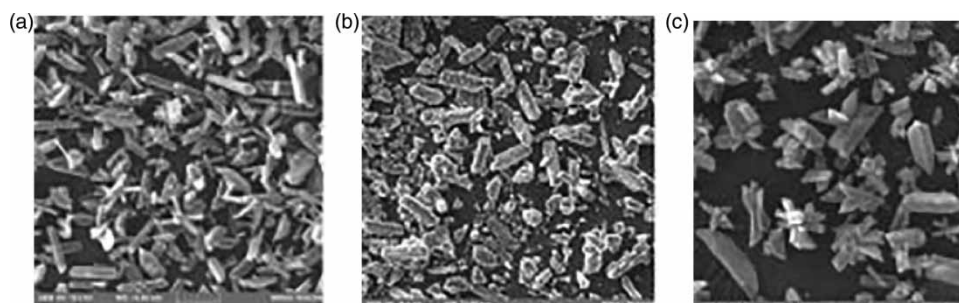


Figure 5 | SEM photograph of struvite crystals: (a) Mg/Ca ratio of 1:0, (b) Mg/Ca ratio of 1:1, and (c) Mg/Ca ratio of 1:2 (Moragaspiya *et al.* 2019).

struvite crystal (Le *et al.* 2005). The presence of Ca during struvite precipitation does not affect phosphorus recovery but greatly affect the purity of the struvite.

4. METHODS OF MITIGATING THE EFFECTS OF CALCIUM

As a means of mitigating the negative impact of Ca, the following measures have been identified in the literature.

1. Increasing the concentration of ammoniacal nitrogen ($\text{NH}_4\text{-N}$) in the solution (Moragaspiya *et al.* 2019; Shaddel *et al.* 2020). Struvite purity has shown a significant increase when the concentration of $\text{NH}_4\text{-N}$ is increased. Moragaspiya *et al.* (2019) showed that struvite purity can increase by 5.2% when the concentration of $\text{NH}_4\text{-N}$ is doubled. In their study, a synthetic solution was prepared to mimic wastewater effluent. In their results, when Mg/Ca is 1:1, the % weight of the struvite produced was 68.11, 73.31, and 76.75 at $\text{NH}_4\text{-N}$ concentrations of 328, 700, and 1,000 mg/L, respectively. Crutchik & Garrido (2011) established that when $\text{NH}_4\text{-N}$ is high, factors that favour struvite precipitation over Ca

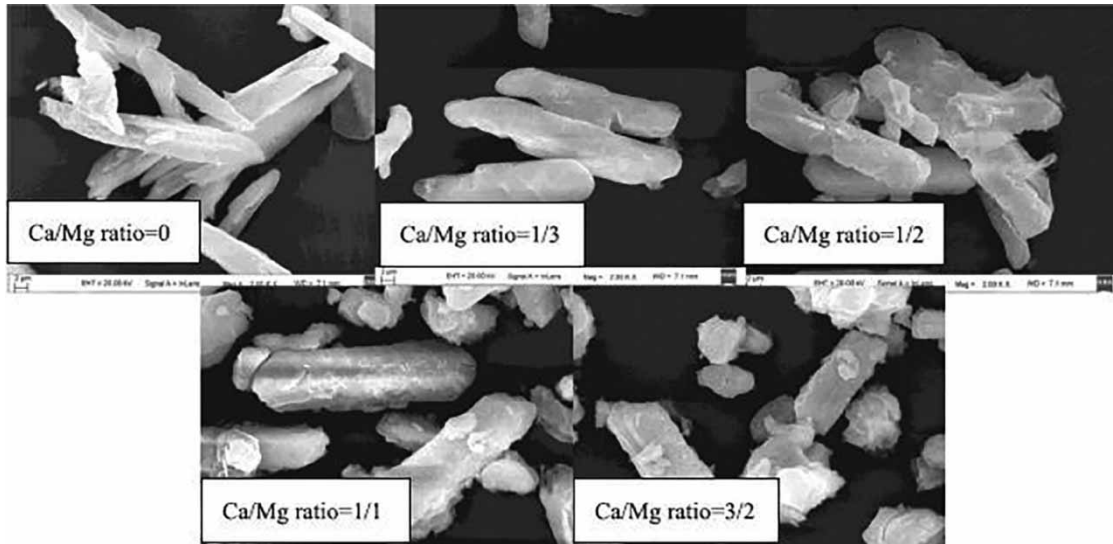


Figure 6 | SEM photograph showing shapes of struvite crystals at different Ca/Mg ratios (Liu & Wang 2019).

- phosphate precipitation like buffer capacity of the solution and nucleation rate of the solution are favoured. Moragaspiya *et al.* (2019) also confirmed that $\text{NH}_4\text{-N}$ acts as a pH buffer by preventing the reduction of pH during struvite reactions.
2. Shaddel *et al.* (2020) studied the effect of a high Mg/P ratio to mitigate the impact of Ca on struvite quality. When Mg/P is kept high (1.67:1, 2.3:1, and 3.1:1) at high pH, the concentration of Ca is kept constantly under 1% in the precipitate produced.
 3. Ye *et al.* (2011) have investigated pH control as a mitigating factor and plotted the percentage amorphous calcium phosphate (% ACP) and the ratio of saturation index of ACP to saturation index of struvite ($\text{SI}_{\text{ACP}}/\text{SI}_{\text{MAP}}$) against pH, as shown in Figure 8. They established that the presence of Ca increased the SI_{ACP} and as a result the % ACP. When the pH is kept at 9.5 and below, the % ACP was kept at an extremely low concentration. The pH adjustment was done along with keeping the Mg concentration in seawater (the Mg source used for the study) at 1% and above.
 4. The mitigating factor of a high Mg/Ca ratio has been suggested by many investigators (Liu *et al.* 2013; Li *et al.* 2019a, 2019b; Moragaspiya *et al.* 2019; Shaddel *et al.* 2020). Adjusting the Mg/Ca ratio during struvite precipitation has been widely used to mitigate the negative effect of Ca.

Struvite purity falls below 60% (Figure 9) when the ratio of Ca/Mg is 1 but can be as high as 90% if the Ca/Mg ratio is 0.5 or less. This was confirmed by Kemacheevakul *et al.* (2014) in their study on the improvement of purity in struvite recovered from hydrolysed urine. This is very important if struvite precipitation is to be an economically viable venture. To increase the purity means adding more Mg to the process to compensate for the presence of Ca but this may not be an economically prudent venture. This means that a very high concentration of calcium in wastewater makes struvite precipitation unfeasible, as it lowers the purity significantly. Struvite purification with regard to calcium removal has not received the attention given to the economic value of the product.

5. NUTRIENT REMOVAL EFFICIENCIES USING DIFFERENT MAGNESIUM SOURCES

Generally, the recovery of $\text{PO}_4\text{-P}$ is calculated by using the following equation:

$$\% \text{ Recovery of P} = \frac{\text{Initial [P]} - \text{Final [P]}}{\text{Initial [P]}} \times 100$$

The presence of Ca^{2+} does not affect the percentage recovery of nutrients from wastewater. Zhang *et al.* (2015) observed that high phosphorus recovery reached a maximum of 95% (Figure 11) at the Mg/Ca molar ratio of 7:1. It was further

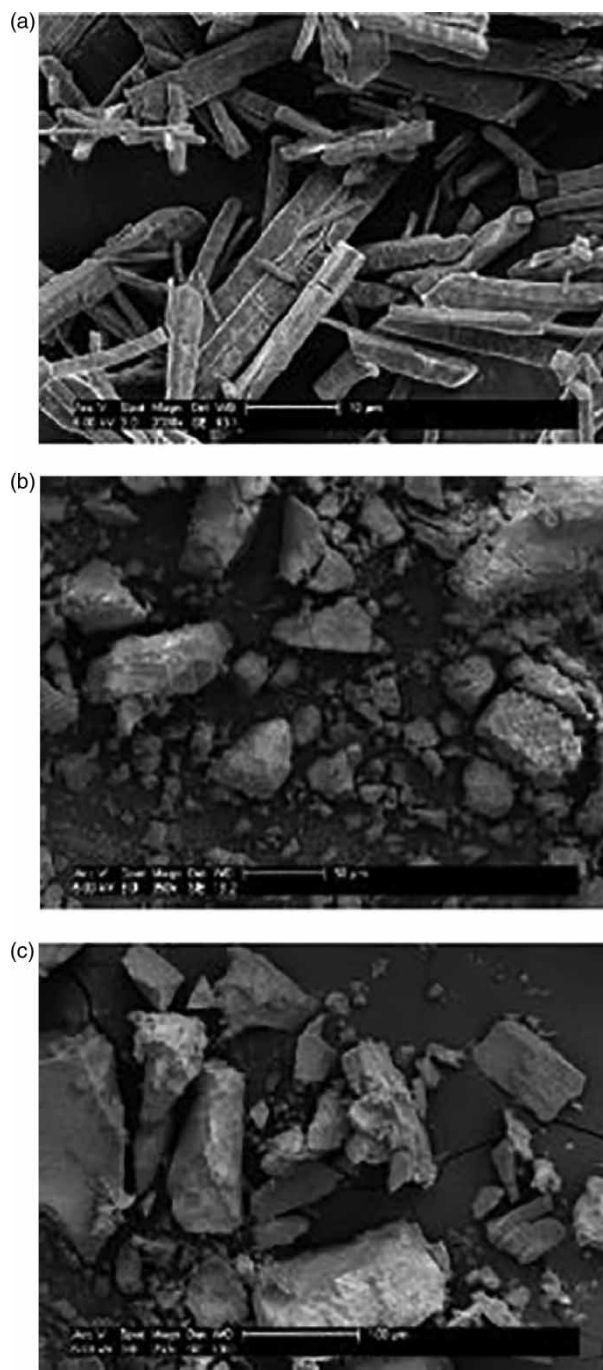


Figure 7 | SEM photograph showing shapes of struvite crystals at different Ca/Mg ratios: (a) Mg/Ca ratio of 1:0, (b) Mg/Ca ratio of 1:1, and (c) Mg/Ca ratio of 1:2 (Le *et al.* 2005).

observed that the struvite content of the precipitate formed was only 17%. However, pH, Mg/P molar ratio, and reaction time are the significant factors that affect $\text{PO}_4\text{-P}$ recovery.

$\text{PO}_4\text{-P}$ recovery can occur between the pH of 7– and 11 but lower % $\text{PO}_4\text{-P}$ are removed at pH lower than 8 as can be seen in Figure 10. Mijangos *et al.* (2004) has been corroborated by Pastor *et al.* (2008) in an experiment conducted to determine the conditions influencing struvite precipitate. They observed that when pH was gradually increased from 8.2 to 9.5, at almost the same reaction time, % $\text{PO}_4\text{-P}$ recovery changed from 37.3 to 76.1%, respectively. Huang *et al.* (2017) attributed this reason to

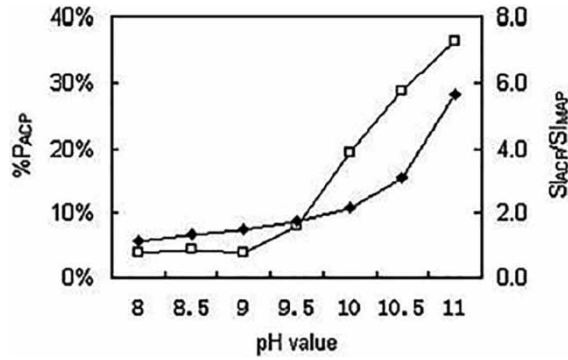


Figure 8 | Percentage of phosphorus precipitated as ACP and the ratio of SI_{ACP}/SI_{MAP} (Ye *et al.* 2011).

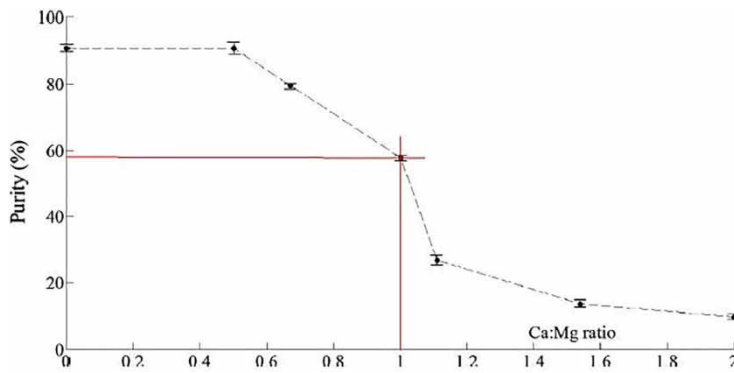


Figure 9 | Influence of calcium on struvite purity (Li *et al.* 2016).

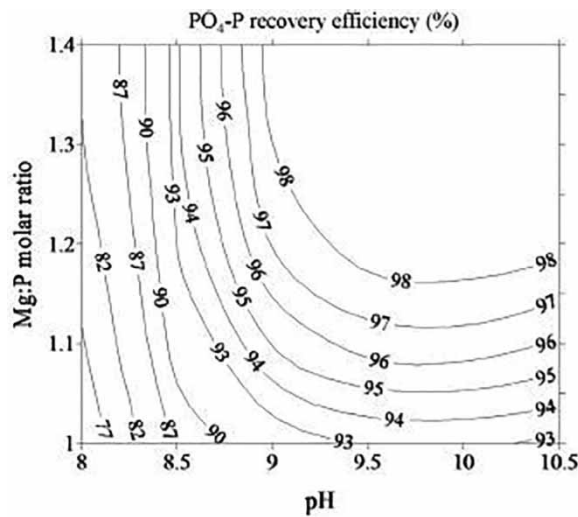


Figure 10 | Influence of pH and Mg/P molar ratio on P recovery (Huang *et al.* 2017).

orthophosphate speciation at different pH. At low pH of 8, there is a lower quantity (87%) of HPO_4^{2-} in the total orthophosphate, while the proportion of HPO_4^{2-} increases significantly (99%) at pH 9. This is likely to be the reason why PO_4 -P recovery as struvite is high at high pH values. Interestingly, Zhang *et al.* (2015) in their study on phosphorus recovery from bioeffluents of wastewater treatment plant (WWTP) observed that a rather huge drop in phosphorus recovery occurred at pH beyond 11.

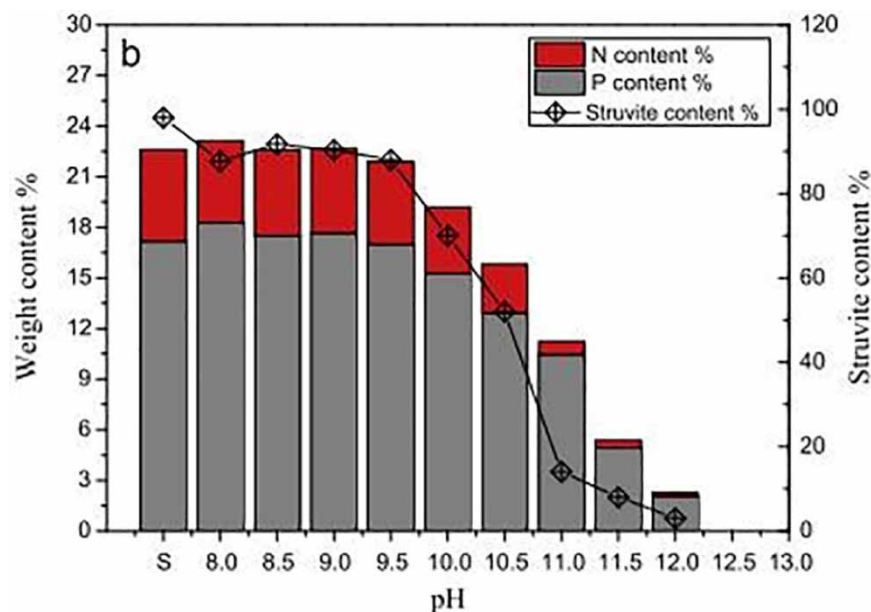


Figure 11 | Influence of pH on phosphorus recovery at the Mg/Ca ratio of 7:1 (Zhang *et al.* 2015).

The molar ratio (specifically Mg/P molar ratio) of participating ions during struvite precipitation is very important because it affects the level of the solution. Recovery of total phosphorus (TP) is very high at a high Mg/P molar ratio (Table 2). Ye *et al.* (2016) observed that TP recovery increases significantly when the Mg/P ratio is 1.8 and above. Korchef *et al.* (2011) explained that an increase in Mg concentration in solution decreases the adhesion of crystals on the walls of the reactor vessel which result in high $\text{PO}_4\text{-P}$ recovery.

From Table 2, it can be seen that high-grade Mg sources (e.g. MgCl_2 and MgSO_4) can be replaced by natural Mg-rich sources in the production of struvite. However, strategies must be adopted to improve reactivity and removal of impurity

Table 2 | Percentage of phosphorus recovery at different operational conditions from different Mg sources

Mg source	Wastewater type	Operational conditions			% phosphorus recovery	References
		pH	Reaction time	Mg/P ratio		
MgCl_2	Synthetic	8.8	30 min	–	> 90.0	Aguado <i>et al.</i> (2019)
Seawater	Synthetic	8.8	30 min	–	88.9	
Dolomite	Synthetic	8.0	2 h	1:1.2	75.7	Chen <i>et al.</i> (2017)
MgO	Synthetic	9.0	10 min	2:1	90–99	Barbosa <i>et al.</i> (2016)
MgCl_2	Synthetic	8.0	10 min	2:1	89	
$\text{Mg}(\text{OH})_2$	Synthetic	8.7	10 min	1.5:1	93	
MgCl_2	Swine	8.5	–	1.5	71.1–75.7	Wang <i>et al.</i> (2018)
MgSO_4	Swine	8.5	–	1.5	75.7	
Brine	Swine	8.5	–	1.5	71.1	
Seawater	Anaerobic sludge	8.2	60 min	1	95.1	Lahav <i>et al.</i> (2013)
Seawater	Anaerobic sludge	8.2	20 min	1.12	92.6	
Brine	Urine	9.3	–	1.1:1	99	Liu <i>et al.</i> (2013)
Seawater	Urine	9.3	–	1.1:1	99	
MgCl_2	Urine	9.3	–	1.1:1	99	
WWTP effluent	WWTP effluent	9–9.5	–	1.4:1	97	Zhang <i>et al.</i> (2015)

ions (Ca^{2+}) from both wastewater and Mg sources that have the potential to hinder struvite quality. It can be observed that this reduces the crystal size of the struvite product.

6. CONCLUSION

The literature has shown that the presence of Ca ions in solution during struvite precipitation negatively affects struvite quality, in terms of purity, size, and morphology. All papers reviewed revealed that at higher Ca concentrations, the crystals formed had reduced size and contained amorphous Ca phosphate substances rather than crystalline struvite. Even though Ca negatively affected struvite quality, its presence in solution did not negatively affect $\text{PO}_4\text{-P}$ removal from wastewater irrespective of the type of Mg source used. $\text{PO}_4\text{-P}$ recovery was rather affected by pH, Mg/P molar ratio, and reaction time. The high percentage recovery of P is always achieved at a higher Mg/P molar ratio. Even though the effect of Ca in solution during struvite precipitation has been studied, gaps still exist in the area. Research must be carried out on the removal of only Ca from Mg-rich sources to improve struvite purity, size, and thus its use as a fertiliser. The selective removal of Ca before struvite precipitation is a research gap that must be explored. Also, struvite precipitation from low phosphorus-rich sources should be looked at, since most research is focused on phosphorus-rich wastewater.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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