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NUTRIENT RECOVERY FROM FOOD-GRADE WASTEWATER EFFLUENTS THROUGH STRUVITE CRYSTALLIZATION PROCESS AND ITS APPLICATION AS A FERTILIZER FOR CROPS IN BIKANER

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ABSTRACT
Food industries in the Bikaner region generate substantial quantities of wastewater containing huge organic and nutrient loads, creating noticeable environmental challenges in arid and water-scarce areas. This study evaluates wastewater from selected food-grade industries by analysing major physicochemical parameters, including biochemical oxygen demand, chemical oxygen demand, total suspended solids, nitrogen, and phosphorus. That's high concentrations of organic pollutants and nutrients, indicating the necessity for efficient treatment and sustainable resource recovery approaches. To address this issue, struvite precipitation was investigated as a nutrient recovery technique for ammonia-rich industrial effluents. The effects of parameters such as pH, mixing speed (RPM), and retention time on struvite crystallisation efficiency were systematically examined. The recovered precipitate was confirmed as struvite through X-ray diffraction (XRD) analysis. The study demonstrated that struvite precipitation effectively reduces nutrient pollution while converting wastewater-derived nutrients into a slow-release fertiliser. The findings contribute to the growing field of sustainable wastewater management and circular economy practices by demonstrating a practical method for simultaneous pollution control and resource recovery. This research provides a foundation for future studies on industrial wastewater valorisation and supports the development of environment-friendly treatment technologies suitable for semi-arid regions. The outcomes may assist industries, researchers, and policymakers in promoting sustainable industrial practices, nutrient recycling, and environmental protection in regions facing increasing water and waste management challenges.
Keywords: Bikaner, Circular Economy, Food Processing Industry Effluent, Nutrient Recovery, Sustainable Practices.

INTRODUCTION

The furious growth of the food processing industry in India has significantly increased the generation of industrial wastewater, especially in water-scarce and environmentally sensitive regions. Food-grade industries such as dairy processing, snack manufacturing, sweet production, pickle formation, and other agro-based units consume large quantities of water during washing, cleaning, cooling, and processing operations, thereby generating wastewater rich in organic and inorganic pollutants.[1-3] In semi-arid and arid states such as Rajasthan, improper disposal of industrial effluents poses serious environmental concerns due to limited freshwater availability and fragile ecological conditions. Bikaner has emerged as a major centre for food-grade industrial activities in Rajasthan, located at 28.0229° N latitude and 73.3119° E longitude. The district experiences arid climatic conditions characterised by low annual rainfall, high evaporation rates, extreme temperatures, and poor groundwater recharge. The expansion of food processing industries in Bikaner has contributed considerably to economic development and employment generation; however, it has simultaneously increased the effluent of industrial wastewater into the surrounding area. Untreated or partially treated wastewater from these industries may

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contaminate both surface water and groundwater resources, which are already limited in arid regions.[3-7] Food industry effluent generally contains high concentrations of biochemical oxygen demand, chemical oxygen demand, total suspended solids, nutrients, oils, and grease [1,18] The outlet of such high nutrient level wastewater into the environment may lead to eutrophication, oxygen depletion, foul odour generation, and deterioration of aquatic ecosystems. In addition, elevated concentrations of nitrogen and phosphorus present in industrial effluents contribute significantly to environmental pollution and ecological imbalance.[4,15] Therefore, the development of sustainable wastewater treatment technologies capable of simultaneous nutrient removal and resource recovery has become an important area of research.[18] Conventional wastewater treatment methods, such as activated sludge processes, coagulation-flocculation, oxidation, membrane filtration, and anaerobic digestion, are widely used for industrial effluent treatment. However, many of these techniques are associated with high operational costs, sludge generation, energy requirements, and limited nutrient recovery efficiency.[21,36] In recent years, resource recovery-based wastewater treatment technologies have gained increasing attention due to their environmental and economic benefits. Among these technologies, struvite crystallisation has emerged as a sustainable treatment method for nutrient removal and extraction from wastewater streams.[6,8] Struvite is a magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4 \cdot 6H_2O$), which is obtained by the crystallisation of magnesium, ammonium, and phosphate ions under alkaline conditions.[2,6] The crystallisation formation reaction occurs according to the following equation.[6,40]

$$Mg^{2+} + NH_4^{+} + H_nPO_4^{3-n} + 6H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O + n\,H^{+} \quad \text{.....(1)}$$

The formation of struvite takes place when the ionic concentrations like magnesium, phosphate and ammonia exceed the solubility product of the mineral, resulting in the precipitation of ammonium and phosphate as crystalline solids.[25] Several operational parameters such as pH, temperature, Super saturation level, and molar ratio of magnesium to. Among these factors, pH plays a crucial role in nucleation and crystal growth, with optimum precipitation generally observed in the alkaline range of pH 8–10.[13,19] Struvite precipitation provides multiple environmental and economic advantages because it enables simultaneous nutrient removal and fertiliser recovery from wastewater.[8] Obtained struvite crystal product acts as a slow nutrient release fertiliser suitable for agricultural and horticultural applications due to struvite's low solubility and gradual nutrient release properties.[2,17,24] Previous studies have reported that struvite recovery can significantly reduce nitrogen and phosphorus concentrations in wastewater while converting waste nutrients into valuable products.[16,21,26] This approach supports the principles of sustainable nutrient management by promoting nutrient recycling and reducing dependence on conventional chemical fertilisers.[17,35] Another important advantage of controlled struvite precipitation is the prevention of uncontrolled scaling in wastewater treatment systems. Uncontrolled struvite deposition inside pipelines, pumps, reactors, and sludge handling equipment can lead to severe operational and maintenance problems in treatment plants.[27] Therefore, controlled recovery of struvite not only improves wastewater treatment efficiency but also minimises scaling-related issues and operational costs.[29] Extensive research has been carried out on struvite crystallisation, including studies related to crystal chemistry, thermodynamics, kinetics, operational optimisation, and recovery efficiency.[22,23,25,37,38] Several researchers have also investigated advanced methods such as electrochemical and electrocoagulation-assisted struvite crystallisation for enhanced nutrient recovery from industrial and municipal wastewaters.[10,33] Recent studies have highlighted the efficiency of struvite precipitation as a efficient and sustainable method for nutrient recovery from high organic load wastewater streams.[9,30,36] Despite considerable advancements in nutrient recovery technologies, limited studies have specifically focused on the treatment of food-grade industrial effluents generated in arid regions such as the Bikaner district, Rajasthan.[42] The unique wastewater characteristics of food processing industries, combined with severe water scarcity and environmental sensitivity of the region, necessitate the development of an effective and sustainable treatment idea. So the this study targets to evaluate the applicability of struvite crystallisation precipitation for nutrient elimination and resource recovery from food-grade industrial wastewater effluent generated in Bikaner district. The study further investigates the influence of struvite

crystallisation operational parameters on struvite crystal formation and assesses the potential utilisation of obtained struvite, such as a sustainable slow-release crystal fertiliser for environmental and agricultural applications.[4,8,12,30]

Research Gap

Although previous studies have reported the effectiveness of struvite precipitation for nutrient recovery from municipal wastewater, landfill leachate, swine wastewater, and anaerobic digestion systems, limited research has specifically focused on food-grade industrial wastewater generated in arid and semi-arid regions like Bikaner.[2,6,8,15,22,28,41]

EXPERIMENTAL

Study Area

Bichwal Area, Karni Industrial Area and Rani Bazar Industrial Area. These food-grade industries generate a high level of organic matter, oil & grease, starch, nutrients, and salts due to large-scale food processing activities such as bhujia, namkeen, sweets, papad, and snack production. Previous observations indicated comparatively high Chemical Oxygen Demand, Biological Oxygen Demand, Total Dissolved Solids, phosphate, and nitrate concentrations in untreated influent before ETP treatment; therefore, these wastewater samples were selected for experimental investigation.

Sample Collection

Wastewater effluent samples were collected from five food-grade industries in the arid zone of the Bikaner region and analysed for their physicochemical characteristics. Based on preliminary analysis, Industries 4 and 5 were selected for further study due to their higher pollution levels, particularly elevated BOD, COD, ammonia, and phosphate concentrations. Industry 4 contained 3.3 mg/L ammonia, while Industry 5 showed a much higher concentration of 340 mg/L, as shown in Table-1, representing moderate and high-strength wastewater, respectively. For struvite precipitation, the wastewater pH was adjusted to 8–9, and magnesium and phosphate sources were added to promote crystal formation. The experiments were conducted at different mixing speeds (RPM) and retention times to assess their effect on nutrient recovery. Parameters such as ammonia, phosphate, and BOD were measured before and after treatment, and struvite formation was confirmed by XRD, with crystal morphology analysed using SEM.

Table-1: Physicochemical Characteristics of Effluents

S.No.	Parameter	Industry effluent 1	Industry effluent 2	Industry effluent 3	Industry effluent 4	Industry effluent 5
1.	pH	7.08	6.89	7.4	4.93	9.0
2.	EC (µS/cm)	1589	1078	1750	1339	10660
3.	TDS (mg/L)	1150	715	1190	888	7012
4.	Total Hardness (mg/L $CaCO_3$)	300	220	270	310	750
5.	COD (mg/L)	120	140	200	1000	2860
6.	Alkalinity (mg/L)	260	210	260	240	1050
7.	Calcium Hardness (mg/L)	160	130	190	170	410
8.	Magnesium Hardness (mg/L)	140	90	80	140	340
9.	Chlorides (mg/L)	295	180	380	240	2500
10.	Sulphates (mg/L)	40	71	41	96	284
11.	Nitrates (mg/L)	24	24	9	28	26
12.	Sodium (mg/L)	310	225	355	260	2450
13.	Potassium (mg/L)	15	15	18	14	42
14.	Phosphates (mg/L)	2.5	2.1	2.8	8.66	5.10
15.	Fluoride (mg/L)	1.1	1.2	1.2	1.5	0.9
16.	Ammonia (mg/L)	7.8	8.96	5.1	3.3	340
17.	BOD (mg/L)	30	36	49	225	681

Struvite yield was theoretically calculated based on the stoichiometric reaction of Mg^{2+}, NH_4^+, and PO_4^{3-} in a 1:1:1 molar ratio using the formula $MgNH_4PO_4 \cdot 6H_2O$.[42] In sample 5, available ions, phosphate (PO_4^{3-}) was identified as the limiting reagent 0.0537 m mol/L, resulting in a maximum theoretical struvite precipitation of 13.18 mg/L.

RESULTS AND DISCUSSION

Among the five industries identified, Industries 4 and 5 exhibited comparatively higher pollution loads and were therefore selected for detailed struvite precipitation studies, as mentioned in Table 2. Industry 5 showed extremely elevated concentrations of ammonia (340 mg/L) and BOD (681 mg/L), indicating high-strength effluent typical of food-processing operations, while Industry 4 also showed notable contamination. Application of struvite precipitation resulted in substantial reductions in nutrient and organic pollution parameters in both effluents. In Industry 4, ammonia decreased from 3.3 to 0.7 mg/L, phosphate from 8.66 to 1.2 mg/L, and BOD from 225 to 40 mg/L. Similarly, Industry 5 exhibited a marked reduction in ammonia (340 to 37 mg/L), phosphate (5.10 to 1.0 mg/L), and BOD (681 to 180 mg/L). These reductions confirm the effect of struvite precipitation in simultaneously removing nitrogen, phosphorus, and biodegradable organic matter.

Table-2: Presents the Comparative Pre and Post-Treatment Values for Industries 4 and 5

S.NO.	Parameter	Industry 4 (pre struvite treatment)	Industry 4 (post struvite treatment)	Industry 5 (pre struvite treatment)	Industry 5 (post struvite treatment)
1	Ammonia (mg/L)	3.1	0.7	340	37
2	Phosphate (mg/L)	8.66	1.2	5.10	1.0
3	BOD (mg/L)	225	40	681	180

Characterisation of the crystal precipitate shows the formation of struvite from effluent is ($MgNH_4PO_4 \cdot 6H_2O$).XRD analysis revealed crystalline peaks corresponding to orthorhombic struvite. The calculated unit cell parameters were a = 6.954 Å, b = 6.140 Å, and c = 11.216 Å, with interaxial angles $\alpha = \beta = \gamma = 90°$, which are reported standard struvite structures.[39,40] while SEM images showed well-defined prismatic crystals. EDS spectra confirmed the presence of magnesium, phosphorus, nitrogen, and oxygen, validating the purity of the obtained product. These results show that nutrient removal occurred primarily through true struvite crystallisation rather than non-specific precipitation. Operational parameters significantly influenced nutrient recovery efficiency. Maximum ammonia and phosphate removal occurred at PH 8.0, moderate mixing (200 rpm), and 1 hour retention time. At PH 7.0, removal efficiency was lower due to limited supersaturation, whereas at PH 9.0, slightly reduced efficiency was observed due to competing magnesium hydroxide formation. Moderate agitation ensured uniform mixing and stable crystal growth, while excessive mixing (400 RPM) likely caused crystal breakage.[8,9,13,14,19,22,23,30]

(a) (b) (c)

Fig.-1: Comparative growth (a) Guar (b) Aloe Vera (c) Spinach

As indicated in Table-3, the effects of optimal pH, RPM, and Retention time on ammonia removal efficiency clearly indicate peak performance at pH 8.0, 200 rpm, and 1 hour of retention time.

Table-3: The Effect of Optimal PH, RPM, and Time on Ammonia and Phosphate Removal Efficiencies by Struvite Crystal Formation

Parameter	Values	Industry 4: % Ammonia Removal	Industry 4: % Phosphate Removal	Industry 5: % Ammonia Removal	Industry 5: % Phosphate Removal
pH	7.0 (neutral)	35%	45%	40%	52%
	8.0 (optimal)	74%	83%	78%	89%
	9.0 (alkaline)	70%	80%	73%	84%
Rotation Speed(RPM)	100	62%	72%	65%	75%
	200 (moderate)	76%	85%	80%	88%
	400 (high)	60%	73%	67%	77%
Time (hr)	0.5	52%	60%	57%	65%
	1.0 (optimal)	75%	86%	80%	90%
	2.0	77%	86%	81%	91%

Deviations from these optimal conditions resulted in a moderate decline in efficiency due to competing reactions, reduced crystal purity, or mechanical disruption of struvite crystals. The Table-4 represents the Comparative Growth Response of Selected Crops Under Control, Chemical Fertiliser, and Struvite Treated Conditions.

Table-4: Comparative Growth Response of Selected Crops Under Control, Chemical Fertiliser, and Struvite Treated Conditions.

S.No.	Plant	Growth Parameter	Control (No Struvite)	Chemical Fertilizer	Struvite Treated
1	Spinach	Plant Length (cm)	18.5	21.3	24.2
		Leaf Number	10	13	15
2	Guar	Plant Length (cm)	22.5	25.9	27.5
		Total Mass (g)	50	61	68
3	Aloe	Leaf Length (cm)	29.4	33.2	36.8
		Leaf Count	8	9	10

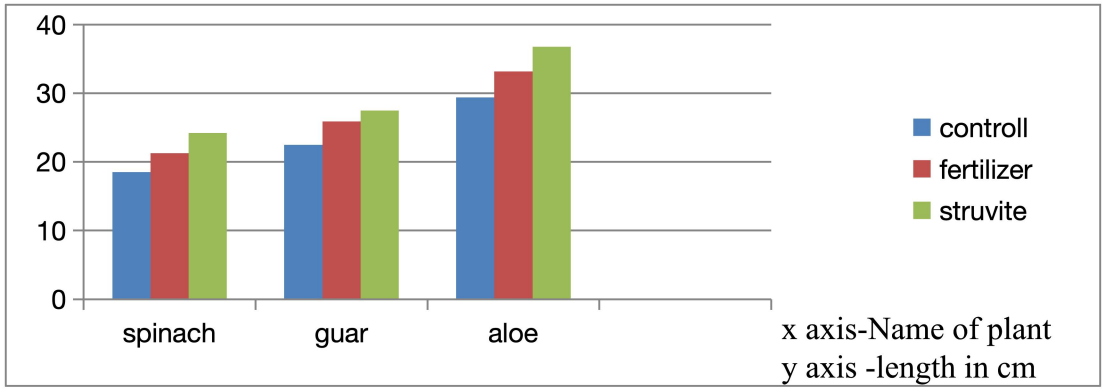

Fig.-2: Effect of Length in Spinach, Guar, Aloe Agriculture Plant by Different Fertilizers Condition Include Struvite

Under optimal conditions (pH 8.0, 200 rpm, 1 hour), phosphate removal exceeded 85–90%, while ammonia removal ranged between 75–85% for both industries. This indicates suitability for practical application with shorter hydraulic retention times. By struvite wastewater treatment, recovered struvite demonstrated significant fertiliser potential. Experiments on spinach, guar, and aloe Vera showed improved plant growth compared to control (blue bar) and conventional fertilisers (red bar), attributed to the slow-release properties of struvite (green bar) and sustained nutrient availability as shown in Fig.-2. Overall, the integrated results demonstrate that struvite precipitation is an efficient and sustainable approach for nutrient recovery from food industry wastewater effluent in arid regions like Bikaner.[42] The process not only reduces environmental pollution but also converts waste-derived nutrients into a valuable slow-release fertiliser, supporting circular economy principles and sustainable agriculture.

Present Study: Comparison with the Previous Study

The comparison on Struvite Crystallisation and Agricultural Application, with the previous studies is mentioned in Table-5, with the given wastewater sources.

Table-5: Previous Studies Compared with Present Studies on Struvite Crystallisation and Agricultural Application

S. No.	Study Reference	Wastewater Source	Major Findings on Struvite Recovery	Agricultural Plant Application	Comparison with the Present Study
1	Doyle and Parsons (2002)	Animal wastewater	Reported efficient phosphorus recovery through struvite crystallisation at alkaline pH conditions.	Suggested use of recovered struvite as a slow-release fertiliser.	The present study similarly recovered nutrients through struvite precipitation from food-grade industrial effluent.
2	Ryu et al. (2008)	Swine wastewater	Found pH and mixing conditions strongly influence struvite formation efficiency.	Improved crop nutrient uptake due to slow nutrient release.	The present study also evaluated pH, RPM, and retention time as major affecting parameters.
3	Rahman et al. (2011)	Municipal wastewater	Obtained high phosphorus recovery and confirmed struvite by XRD analysis.	Enhanced growth of leafy vegetables compared to the control soil.	Similar XRD confirmation was observed in the present study with improved spinach growth.
4	Kataki et al. (2016)	Industrial wastewater	Demonstrated nutrient recovery from industrial effluent under optimised alkaline conditions.	Reported improved biomass production in crops.	The present study extends this approach to food processing industrial wastewater from Bikaner.
5	Li and Zhao (2017)	Synthetic nutrient wastewater	Identified pH 8–10 and controlled agitation as optimum conditions for crystallisation.	Discussed sustainable fertiliser applications.	The present study similarly optimised pH, RPM, and time for efficient nutrient recovery.
6	Present Study (2026)	Food-grade industrial effluent	The struvite yield obtained was 13.18 mg/L from 1 L of wastewater. Recovery efficiency was significantly influenced by pH, RPM, and reaction time. XRD confirmed struvite formation.	Struvite-treated plants showed superior growth over control and chemical fertiliser treatments in spinach, guar, and aloe.	Practical application of circular economy and sustainable wastewater management in arid industrial regions.

CONCLUSION

This study demonstrates that struvite precipitation is a highly effective and sustainable approach for treating food industry wastewater with elevated ammonia and phosphate concentrations in the Bikaner region. The process resulted in significant reductions in ammonia, phosphate, and BOD levels, while also facilitating the recovery of struvite as a valuable by-product. The optimal operational parameters were determined to be a pH of 8.0, a rotation speed of 200 rpm, and a retention time of one hour, under which maximum nutrient removal efficiencies were achieved. Characterisation studies confirmed the successful formation of high-purity crystalline struvite, underscoring its potential for agricultural reuse. The application of the recovered struvite enhanced plant growth and biomass production compared to conventional fertilisers, demonstrating its suitability for sustainable agriculture, particularly in arid regions. So struvite precipitation presents a dual advantage of environmental protection and resource recovery by reducing nutrient pollution and promoting fertiliser sustainability. Its implementation in food-

processing industries can play a significant role in improving wastewater management, facilitating nutrient recycling, and enhancing long-term environmental resilience in water-scarce regions such as Bikaner.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-6, 12:* Struvite Crystallisation and Its Application. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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