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Analysis of the Application Potential of Microbial Flocculant Modification Technology in the Advanced Treatment of Pharmaceutical Wastewater

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Abstract At present, public awareness of environmental protection is gradually increasing, leading to a growing focus on water treatment. The application of microbial flocculants in water treatment can effectively treat microorganisms in various types of wastewater, preventing water sources from being severely polluted and causing adverse effects on the natural environment. To clarify the application potential and influencing factors of different types of microbial flocculants in pharmaceutical wastewater of varying properties, this study employed a meta-analysis method to statistically analyze 339 observational results from 30 articles. Factors such as temperature, pH value, coagulants, and flocculants all influence the effectiveness of microbial flocculants in the advanced treatment of pharmaceutical wastewater. Due to the high content of difficult-to-degrade organic matter in pharmaceutical wastewater, achieving compliance with discharge standards through a single method is challenging. In practical applications, microbial flocculants must be used in conjunction with other treatment processes. In the future, flocculant technologies should be integrated to achieve complementary advantages and address increasingly complex water treatment environments.

Index Terms microbial flocculants, Meta-analysis, pharmaceutical wastewater, statistical analysis

I. Introduction

Pharmaceutical wastewater poses a significant challenge in the field of industrial wastewater treatment, characterized by poor biodegradability, large pH fluctuations, high nitrogen and phosphorus content, significant water quality variations, complex water composition, dark coloration, large fluctuations in water volume, and the presence of a large amount of high-concentration, difficult-to-degrade organic pollutants. These organic components often exhibit biological inhibitory properties, leading to environmental pollution [1]-[4]. Water quality varies significantly across different production stages and time periods. The average chemical oxygen demand (COD) of pharmaceutical wastewater from major production stages ranges from 5,000 to 60,000 mg/L, while the biochemical oxygen demand (BOD) ranges from 750 to 10,800 mg/L [5], [6]. It is evident that the difficulty in treating pharmaceutical wastewater lies not only in its high organic matter concentration but also in its poor biodegradability.

Generally, wastewater treatment plants within pharmaceutical company premises can remove approximately 90% of the COD from the raw water. Once the wastewater meets the relevant discharge standards, it is often routed through the drainage network to the industrial park wastewater treatment plant for further treatment [7], [8]. After treatment at the on-site wastewater treatment plant, the biodegradability of the wastewater is often even lower, while total nitrogen and total phosphorus concentrations remain at relatively high levels [9], [10]. This results in two issues: first, the influx of pharmaceutical industrial wastewater may exceed the original design capacity of the wastewater treatment plant; second, if the industrial park has a large volume of pharmaceutical industrial wastewater, and the quality and quantity of domestic wastewater are insufficient to offset this impact, it will disrupt the operation of the subsequent wastewater treatment plant [11]-[13]. In such circumstances, where wastewater from industrial zones dominated by pharmaceutical wastewater cannot be effectively treated, advanced treatment is necessary. After traditional anaerobic and aerobic two-stage biological treatment, the COD of pharmaceutical wastewater remains at 500–600 mg/L, failing to meet discharge standards [14]. Currently, companies typically employ methods such as flocculation precipitation, adsorption, iron-carbon microelectrolysis, and Fenton oxidation for advanced treatment to meet industrial park discharge standards. However, these methods not only generate secondary pollutants but also incur high treatment costs, which are detrimental to corporate sustainable development [15]-[18]. Therefore, developing a deep treatment technology for antibiotic wastewater that is low-cost, easy to operate, highly effective, and capable of continuous operation is of great significance for ensuring the high-quality development of the pharmaceutical industry.

Microbial flocculants are a class of metabolic products produced by microorganisms that possess flocculant activity, primarily including glycoproteins, polysaccharides, proteins, cellulose, DNA, and microbial cells with flocculant activity [19]. This flocculant is a novel, efficient, and inexpensive water treatment agent obtained through biotechnology, specifically microbial fermentation, extraction, and purification. It is a non-toxic biological polymer compound that can serve as a new type of water treatment agent, featuring safety, efficiency, ease of biodegradation, no secondary pollution, broad applicability, unique decolorization effects, and relatively low dosage requirements [20]-[23]. Microbial flocculants demonstrate significant advantages in pharmaceutical wastewater treatment, and the formulation is continuously being improved. Literature [24] applied modified microbial flocculants in a mixed aerobic granular sludge membrane system to reduce membrane fouling and enhance wastewater reuse. Literature [25] reported that under co-culture conditions of Bacillus clausii, a probiotic bacterium producing surfactants, and Bacillus amyloliquefaciens, a starch-degrading bacterium, the surfactants generated could effectively remove tetracycline from water. Reference [26] introduced ammonium cerium into chitosan to prepare a modified chitosan flocculant, which, when combined with powdered activated carbon, can effectively remove small-molecule drugs such as ibuprofen and acetaminophen from water contaminated with drug complexes. Reference [27] produced three moderately hydrophobic chitosan flocculants, which demonstrated remarkable efficacy in the treatment of surface water contaminated with antibiotic compounds, achieving removal efficiencies 68.7% higher than commercially available flocculants. Reference [28] used phenylalanine to prepare modified chitosan flocculants, which enhanced the removal efficiency of trace antibiotics in turbid water from kaolinite suspensions and carbon nanotube suspensions. Reference [29] noted that radiation-induced modified chitosan significantly improved the removal efficiency of drugs, dyes, and metal ions in wastewater, addressing issues such as high reagent consumption and uneven modification in traditional chemical modification methods.

The ability of different types of microbial flocculants to remove various indicators from pharmaceutical wastewater is uncertain, so it is necessary to clarify the application potential and influencing factors of different types of microbial flocculants in pharmaceutical wastewater of different properties. This study employed a meta-analysis method to investigate the removal potential of different types of microbial flocculants for organic carbon and nutrient elements in pharmaceutical wastewater. Under optimal flocculation conditions, microbial flocculants were used to treat pharmaceutical wastewater, and the treatment effectiveness of microbial flocculants on pharmaceutical wastewater was evaluated. This provides more comprehensive, in-depth, and guidance-oriented theoretical basis for clarifying the intrinsic relationship between different types of flocculants and various pharmaceutical wastewater streams, as well as accurately determining the most suitable flocculant types for wastewater with different physicochemical properties and environmental factors.

II. Materials and Methods

II. A. Data Sources

The literature included in this study was retrieved from the following databases: China National Knowledge Infrastructure (CNKI), Web of Science, and ScienceDirect. Searches were conducted using keywords such as “microbial flocculants,” “pharmaceutical wastewater,” and “wastewater treatment.” Relevant literature on the impact of microbial flocculant modification technology on advanced wastewater treatment was collected up to 2024. The initially retrieved relevant literature was screened according to the following principles:

(1) The experimental location was within China, the background values of the wastewater were measured prior to the experiment, and the experimental method involved microbial flocculant modification. (2) The experiment must have at least two treatment groups: microbial flocculant modification treatment and no treatment (control group), with each treatment group having at least three replicates, and all other experimental conditions kept consistent. (3) Extractable experimental data included sample means, sample sizes, standard deviations, or standard errors. Based on the above criteria, the screened literature was organized and categorized to establish a literature information database. If the data in the literature was presented in the form of statistical graphs, GetData Graph Digitizer was used to digitize the images. Finally, 339 valid data points from 30 eligible literature sources were categorized and summarized to form the database for this study.

II. B. Data grouping

To ensure the accuracy of the results, each subgroup contains at least three data points. The physical and chemical indicators of wastewater included in the database are mainly: organic matter content, bulk density, water-stable aggregates, total nitrogen content, total phosphorus content, total potassium content, alkali-hydrolyzable nitrogen content, available phosphorus content, available potassium content, and pH value. Soil total Cu, total Cd, total Pb, total Zn, total As, total Cr, available Pb, and available Cd content.

Based on the deep treatment methods of pharmaceutical wastewater using microbial flocculant modification technology, it is divided into two subgroups: direct utilization of microbial cells and microbial cell metabolic products. The overall removal rate of pharmaceutical wastewater treatment plants is grouped by process type for meta-analysis [30]. Processes appearing in more than three literature sources are grouped separately, while those appearing in fewer than three literature sources are grouped under the corresponding process category. Removal rates were grouped by primary treatment, secondary treatment, and tertiary treatment. The removal rates of each process unit (structure or combination of structures) were grouped based on individual structures or combinations of structures.

II. C.Data Analysis

The data included in the study should include the sample mean $\bar{X}$, sample size n, and sample standard deviation SD. If the standard error SE is provided in the literature, then the conversion relationship between the standard deviation and the standard error is:

$$SD = SE \times \sqrt{n} \tag{1}$$

If the pH value is determined using the $CaCl_2$ solution method, convert it uniformly to the pH value determined using water:

$$pH\ value(H_2O) = 1.65 + 0.86\ pH\ value(CaCl_2) \tag{2}$$

In cases where the organic matter and organic carbon indicators of pharmaceutical wastewater vary, the Bemmelen index is used to convert the organic carbon content of pharmaceutical wastewater into the organic matter content of pharmaceutical wastewater:

$$SOM = SOC \times 1.724 \tag{3}$$

In order to eliminate differences in the magnitude of experimental indicators between different studies and to compare treatment effects more intuitively, the response ratio can be used as a method for measuring the magnitude of the effect:

$$RR_i = \ln\left(\bar{X}_t / \bar{X}_c\right) = \ln\left(\bar{X}_t\right) - \ln\left(\bar{X}_c\right) \tag{4}$$

In the formula: RR_i is the response ratio of the i th study; $\bar{X}_t$ is the average value of the corresponding indicator for the microbial flocculant application treatment; $\bar{X}_c$ is the average value of the corresponding indicator for the treatment without microbial flocculant application. The variance of RR_i is calculated using formula (5):

$$V_{RR_i} = S_t^2 / N_t\ \bar{X}_t^2 + S_c^2 / N_c\ \bar{X}_c^2 \tag{5}$$

In the equation: V_{RR_i} is the variance of the i th research response ratio; N_t, $\bar{X}_t$, and S_t are the sample size, mean, and standard deviation of the corresponding indicators for the microbial flocculant application treatment, respectively; N_c, $\bar{X}_c$, and S_c are the sample size, mean, and standard deviation of the corresponding indicators for the treatment without microbial flocculant application.

The results of the heterogeneity test are one of the reference criteria for selecting between a fixed-effects model and a random-effects model for calculating the response ratio. In k studies, the Q statistic follows a chi-square distribution with $k-1$ degrees of freedom. If $P < 0.05$, and $I^2 > 50\%$, it indicates that the true effects among the studies are unequal, and the random effects model can be considered for calculating the effect size. Therefore, based on the results of the heterogeneity test, it is relatively reasonable to select the random effects model for data synthesis in this study. The $D-L$ method is used to calculate the variance τ^2 among different studies:

$$W_i = 1 / V_{RR_i} \tag{6}$$

$$RR_W = \sum_{i=1}^{n} W_i RR_i \Big/ \sum_{i=1}^{n} W_i \tag{7}$$

$$\tau^2 = \max\left\{0, \left[\sum_{i=1}^{n} W_i (RR_i - RR_W)^2 - (n-1)\right] \Big/ \left(\sum_{i=1}^{n} W_i - \sum_{i=1}^{n} W_i^2 \Big/ \sum_{i=1}^{n} W_i\right)\right\} \tag{8}$$

In the formula: W_i is the weight of the i th study, RR_W is the weighted response ratio of RR_i, n is the number of studies, and τ^2 is the variance between studies. Finally, the random-effects model is used to calculate the weighted response ratio $\overline{RR}$ and standard error $SE(\overline{RR})$ of RR_i, and the variance τ^2 between studies is used to reallocate weights:

$$W_i^* = 1/(V_{RR_i} + \tau^2) \quad (9)$$

$$\overline{RR} = \sum_{i=1}^{n} W_i^* RR_i \Big/ \sum_{i=1}^{n} W_i^* \quad (10)$$

$$SE(\overline{RR}) = \sqrt{1 \Big/ \sum_{i=1}^{n} W_i^*} \quad (11)$$

In the formula: W_i^* is the weight calculated for the i th study based on the random effects model; The 95% confidence interval (CI) for $\overline{RR}$ is: $\overline{RR} \pm 1.96 SE(\overline{RR})$, where 1.96 is the two-tailed critical value of the standard normal distribution $(P = 0.05)$. To better compare treatment effects, $\overline{RR}$ is converted to a percentage: Effect size $(\ln RR\%) = [\exp(\overline{RR}) - 1] \times 100\%$. If the 95% CI of $\overline{RR}$ does not intersect the zero line, the null hypothesis that the true response ratio is zero is rejected $(P < 0.05)$, indicating that the treatment effect for the corresponding indicator is significant.

This study analyzed publication bias by calculating the fail-safe number (Fail-Safe N). If N is much greater than the sample size $(N > 5k + 10)$, the results of the included studies are considered reliable. Meta-regression was used to study the relationship between different physicochemical indicators and the latitude, annual average temperature, annual average precipitation, and depth of pharmaceutical wastewater treatment at each experimental site. The meta-analysis was performed using the software OpenMEE.

II. D.Data processing

Data analysis for differences was performed using the Least Significant Difference (LSD) method in SPSS software (P < 0.05). Meta-analysis was performed using the Meta package in R, and figures were generated using Origin 2020 software. Publication bias was analyzed qualitatively and quantitatively using funnel plots and Egger's test. The results showed that the funnel plot was symmetrical and the test value P > 0.05, indicating that there was no publication bias in the collected literature and data.

III. Results and Analysis

III. A. Stability parameter distribution

To ensure data quality, a Gaussian distribution test was used to verify the normality of the weighted response ratio effect values of the average weight diameter of pharmaceutical wastewater treated with microbial flocculant modification technology prior to data processing. Figure 1 shows the distribution of the average weight diameter weight response ratio of pharmaceutical wastewater aggregates. Among the collected data, the average weight diameter values of the aggregates conform to a normal distribution (P < 0.05). The mean value of the average weight diameter weight response ratio of the aggregates is 0.381, primarily distributed between 0.353 and 0.478.

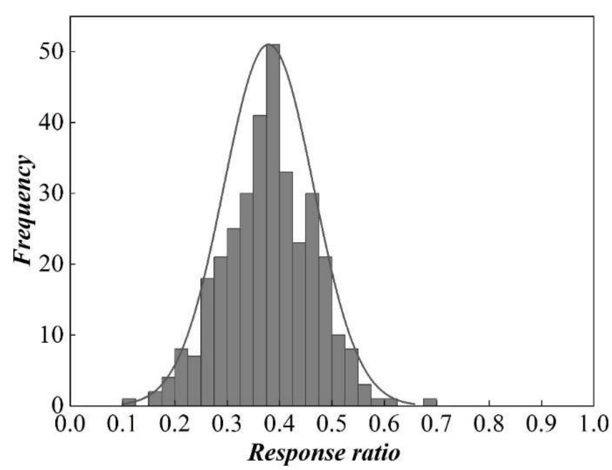


Figure 1: The distribution of the average weight diameter of the drug wastewater reaggregate

III. B. Effect of different types of pharmaceutical wastewater on flocculation efficiency

III. B. 1) Effect of flocculant type on pharmaceutical wastewater

Currently, the flocculation treatment process for pharmaceutical wastewater primarily utilizes three main categories of chemicals: inorganic flocculants, organic flocculants, and composite flocculants. The removal efficiency of different types of flocculants (IF: removal efficiency of inorganic flocculants, OF: removal efficiency of organic flocculants, CF: removal efficiency of composite flocculants, Flo: overall removal efficiency of flocculants) for organic matter and nutrients in pharmaceutical wastewater is shown in Figure 2. TS: Total solids, VS: Volatile solids, COD: Chemical oxygen demand, BOD: Biological oxygen demand, TAN: Ammonia nitrogen, TN: Total nitrogen, TP: Total phosphorus, TK: Total potassium, number of samples.

Overall, compared to no flocculant addition, the addition of flocculants significantly improved the removal rates of various organic matter and nutrients in pharmaceutical wastewater, with TS removal rate increasing by 62.88%, VS removal rate increasing by 71.18%, COD and BOD removal rates increased by approximately 50%, and TAN, TN, TP, and TK removal rates increased by 38.13%, 47.95%, 70.11%, and 22.94%, respectively. Inorganic flocculants demonstrated superior removal efficiency for TS compared to organic flocculants and composite flocculants, with removal rates improved by 21.08% and 12.98%, respectively. This is because the high-valent metal ions (such as Fe^{3+} and Al^{3+}) in inorganic flocculants can neutralize the charges of negatively charged suspended particles in water, reduce the particles' ζ-potential, and destabilize them, thereby promoting particle aggregation. Compared to organic flocculants and composite flocculants, inorganic flocculants also achieved the highest removal rates for TK, increasing by 14.38% and 24.05%, respectively. Organic flocculants achieved the highest removal rate for TN, improving by 13.98% and 14.59% compared to inorganic flocculants and composite flocculants, respectively. Under acidic conditions, the carboxyl groups in organic flocculants can ionize hydrogen ions, forming negatively charged carboxylate ions, which react with cationic nitrogen-containing substances (such as NH_4^+) in wastewater through charge neutralization. This helps reduce the electrostatic repulsion between nitrogen-containing particles, promoting particle aggregation and the adsorption of flocculants onto particles. Under alkaline conditions, amino groups accept hydroxide ions to form positively charged ammonium ions, which can undergo charge neutralization reactions with anionic nitrogen-containing substances (such as nitrate and nitrite ions) in wastewater, similarly aiding in the removal of nitrogen-containing substances. The composite flocculant demonstrates excellent removal efficiency across four parameters: VS, COD, TAN, and TP, achieving removal rates of 77.99%, 64.11%, 45.02%, and 82.98%, respectively. The composite flocculant combines the metal ions of inorganic flocculants with the multiple functional groups of organic flocculants, enabling it to remove various substances through complex chemical reactions.

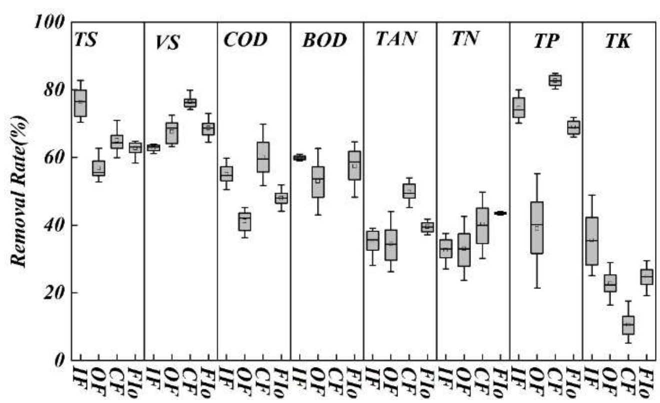


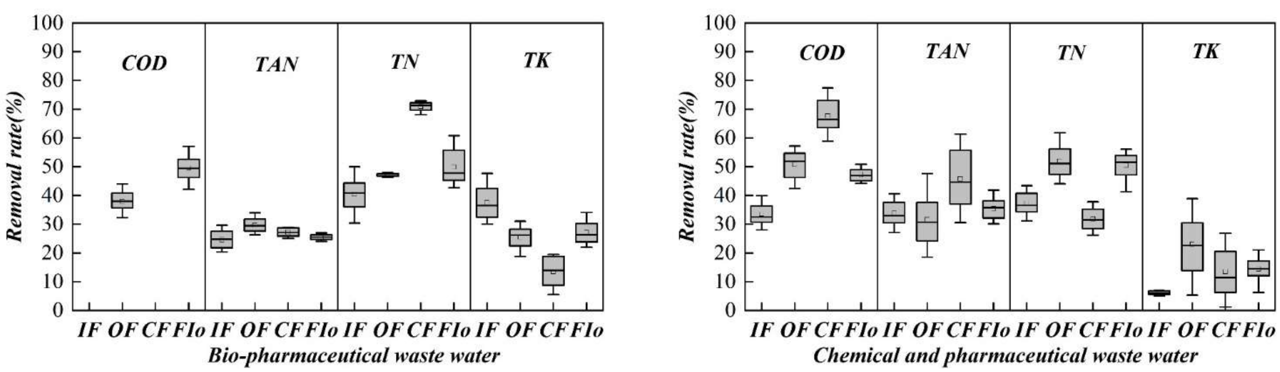
Figure 2: Removal rate of different types of flocculants on the organic matter

III. B. 2) Effect of different types of pharmaceutical wastewater on flocculation efficiency

The results of organic matter and nutrient removal rates for different types of flocculants in biopharmaceutical wastewater and chemical pharmaceutical wastewater are shown in Figure 3. In chemical pharmaceutical wastewater, composite flocculants showed the best removal efficiency for TN, at 68.12%, organic flocculants showed the best removal efficiency for TAN, at 32.58%, and inorganic flocculants showed the best removal efficiency for TK, at 39.89%. Furthermore, in terms of COD removal, the removal efficiency of different types of flocculants was as follows: inorganic flocculants (IF) > organic flocculants (OF). In terms of TAN removal, the removal efficiency of different types of flocculants was as follows: organic flocculants (OF) > inorganic flocculants (IF). In terms of TN removal, the removal efficiency of different types of flocculants was as follows: composite flocculant (CF) > organic flocculant (OF) > inorganic flocculant (IF). In terms of TK removal, the removal efficiency of different types of flocculants was as follows: inorganic flocculant (IF) > organic flocculant (OF) > composite flocculant (CF). Composite flocculants, with their abundant binding sites, can efficiently adsorb suspended solids, nitrifying bacteria, and denitrifying bacteria, demonstrating significant effectiveness in removing nitrogen elements from chemical pharmaceutical wastewater. Organic flocculants exhibit good removal efficiency for TAN. On one hand, flocculants may form chelates with metal ions, indirectly affecting TAN removal. On the other hand, certain metal ions may form complexes with TAN in the wastewater, affecting its stability in the water body. Inorganic flocculants typically do not achieve the highest removal efficiency for TK, but in certain conditions, inorganic flocculants may participate in ion exchange processes, facilitating the exchange of K ions with other ions in the flocculant, thereby removing them.

In biopharmaceutical wastewater, composite flocculants exhibit the best removal efficiency for COD and TAN, while organic flocculants achieve the highest removal efficiency for TN and TK. In terms of COD removal, the removal efficiency of different types of flocculants is ranked as follows: composite flocculants (CF) > organic flocculants (OF) > inorganic flocculants (IF). In terms of TAN removal, the removal efficiency of different types of flocculants is as follows: composite flocculants (CF) > inorganic flocculants (IF) > organic flocculants (OF). In terms of TN removal, the removal efficiency of different types of flocculants is as follows: organic flocculants (OF) > inorganic flocculants (IF) > composite flocculants (CF). In terms of TK removal, the removal efficiency of different types of flocculants is as follows: organic flocculants (OF) > composite flocculants (CF). This may be because composite flocculants may contain components with strong adsorption or chelating capabilities, which can form stable complexes with organic matter or ammonia nitrogen in wastewater. Organic flocculants exhibit the highest removal efficiency for TN and TK, as they may be designed with structures that are easily biodegradable. These flocculants may promote microbial growth in water treatment systems, where microorganisms can utilize part of the dissolved nitrogen as a nutrient source to remove certain forms of nitrogen from TN. Additionally, the flocs formed by organic flocculants may adsorb part of the TK.

Overall, the type of wastewater has a negligible impact on the removal efficiency of nutrient indicators by flocculants and does not exhibit strong correlation. This may be due to significant differences and instability in composition, climate, and cleaning methods, which result in substantial differences in the properties of biopharmaceutical wastewater and chemical pharmaceutical wastewater.



(a) Bio-pharmaceutical waste water (b) Chemical and pharmaceutical waste water

Figure 3: The result of organic matter and nutrient removal rate

III. C. Effect of processing time on stability

The dosage of microbial flocculants has a significant impact on the advanced treatment of pharmaceutical wastewater. This study investigates the effect of treatment time on treatment stability. Figure 4 shows the effect of different treatment durations on wastewater treatment stability. The treatment time of microbial flocculants and the wastewater stability response ratio data exhibit a significant negative correlation, with a linear fitting slope of -0.0038, indicating that for every additional day of treatment, the pharmaceutical wastewater treatment response ratio decreases by -0.0038. This indicates that long-term microbial flocculant treatment can significantly reduce impurities in wastewater within a certain period of time. Compared to long-term treatment without microbial flocculants, the long-term application of microbial flocculants and organic-inorganic co-application significantly increases wastewater treatment stability.

The dosage of microbial flocculants affects soil aggregate stability. Moderate application of microbial flocculants promotes aggregate formation and stability, enhancing water fertility. However, excessive use of microbial flocculants may disrupt particle bonding, leading to salt accumulation and reduced aggregate stability. In this study, compared to untreated conditions, the application of organic-inorganic mixed microbial flocculants significantly improved stability, with the extent of influence first increasing and then decreasing as the dosage increased. Under different microbial flocculant dosage treatments, soil aggregate stability increased with the application of microbial flocculants, and the organic-inorganic mixture treatment showed slightly higher stability than the single microbial flocculant application treatment. Some studies have found that, compared to not using microbial flocculants, within a certain range, the higher the dosage of microbial flocculants applied, the greater the improvement in water body aggregate stability. This indicates that as the dosage of microbial flocculants increases, the stability of water body aggregates also increases accordingly. Long-term use of microbial flocculants significantly increases nitrogen content, and compared to not using microbial flocculants, there is a significant difference in nitrogen distribution between particle size aggregates.

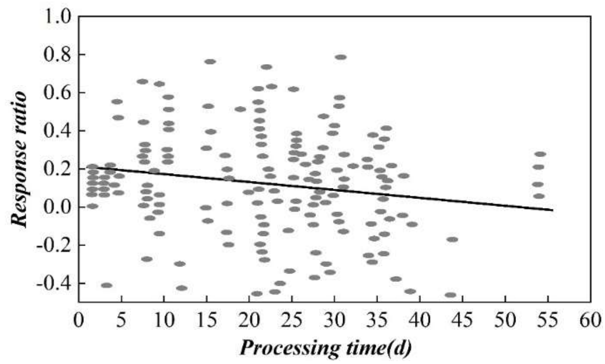


Figure 4: The effect of different processing time on the treatment of wastewater treatment

III. D. Relationship between water stability, physical and chemical properties, and environmental factors

III. D. 1) Relationship between stability and physical and chemical properties

Figure 5 shows the correlation between water body aggregates (BA) and their physicochemical properties [pH, total nitrogen, total phosphorus, total potassium, cation exchange capacity (CEC)]. It can be observed that, with the exception of the positive correlation between aggregates and total nitrogen, all water body aggregates exhibit a significant negative correlation ($P < 0.001$) with physicochemical properties. Among these, wastewater aggregates show a strong positive correlation ($P < 0.001$) with total nitrogen (0.48), while exhibiting weak negative correlations with pH (-0.36), total potassium (-0.65), and cation exchange capacity (CEC) (-0.85) ($P < 0.001$), while showing only a weak negative correlation with total phosphorus (-0.28) ($P < 0.001$). pH shows a strong negative correlation with total nitrogen (-0.66) ($P < 0.001$), a positive correlation with total potassium (0.44) and CEC wastewater cation exchange capacity (0.95) ($P < 0.001$), and no significant relationship with total phosphorus. Total nitrogen in wastewater showed no significant relationship with total phosphorus, but a significant positive correlation with total potassium (-0.48) and CEC wastewater cation exchange capacity (-0.98) ($P < 0.001$). Total phosphorus in wastewater showed a significant correlation with total potassium (0.33) and CEC wastewater cation exchange capacity ($P < 0.001$).

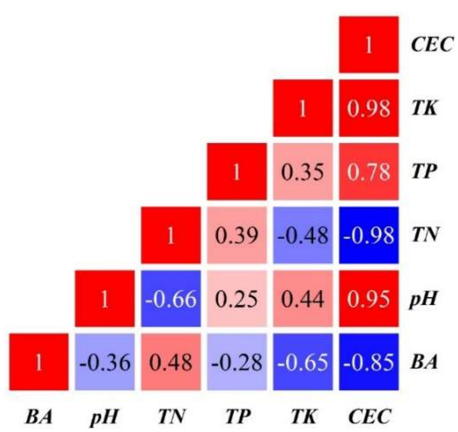
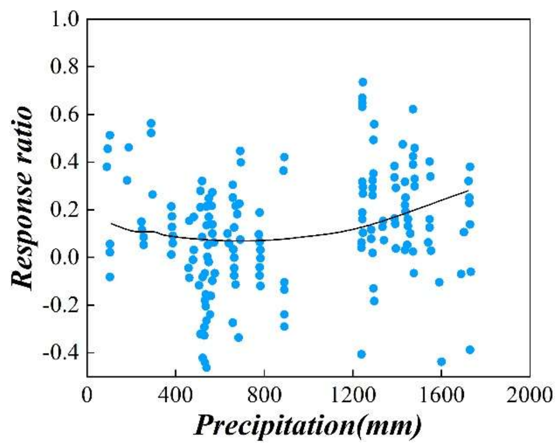


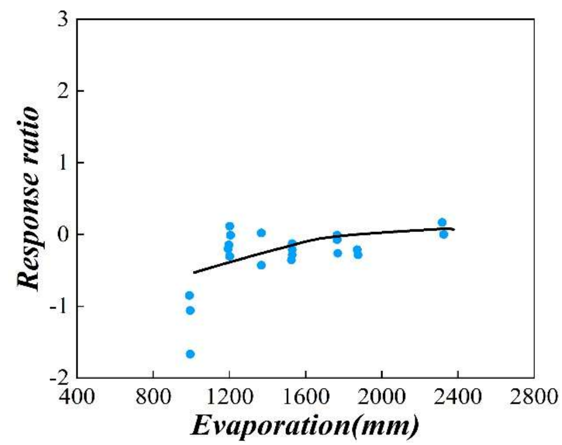
Figure 5: The body of the body is associated with its physical and chemical properties

III. D. 2) Response to environmental factors

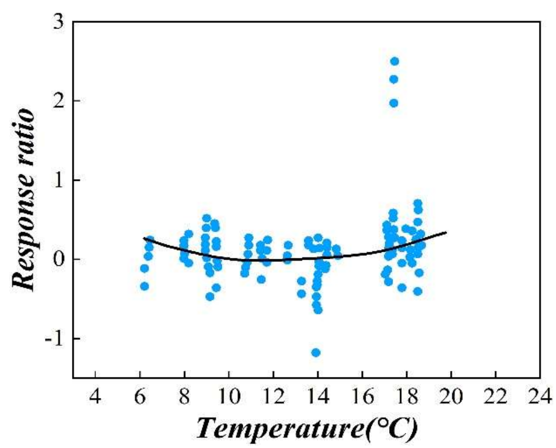
By performing linear regression analysis on the response data of water body aggregates to environmental factors under microbial flocculant treatment conditions, it was found that the response of wastewater aggregates to different environmental factors exhibited a significant positive correlation. Figure 6 illustrates the relationship between the magnitude of change and environmental factors. The relationship between annual average precipitation and effect values (Figure a) shows that as annual average precipitation increases, the aggregation first decreases and then increases with precipitation, exhibiting a significant correlation ($P < 0.05$). Therefore, annual average precipitation is directly correlated with soil aggregation. Relationship between annual average evaporation and effect value (Figure b): As annual average evaporation increases, soil aggregates continue to rise slowly with evaporation, showing a significant correlation ($P < 0.05$). Therefore, annual average evaporation is correlated with wastewater aggregates. The relationship between annual average temperature and effect value (Figure c): As annual average temperature increases, the effect value first decreases slowly and then shows a slow upward trend at 12°C. Soil aggregate size is significantly correlated with average temperature ($P < 0.05$). The relationship between wastewater depth and effect value (Figure d): No correlation is observed from the figure.



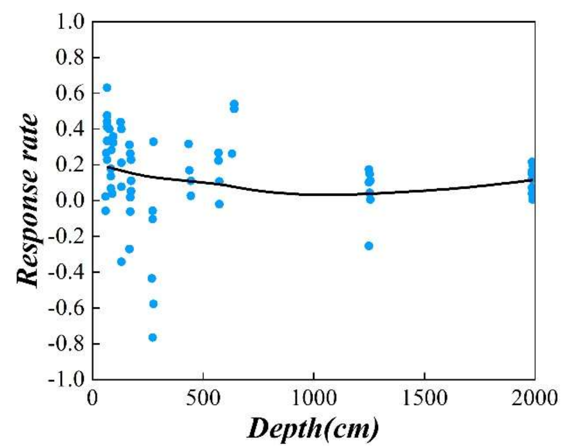
(a) Precipitation



(b) Evaporation



(c) Temperature



(d)Depth

Figure 6: The correlation between variation and environmental factors

The properties of wastewater, such as texture, organic matter content, and pH, determine the stability of flocs. Pharmaceutical wastewater tends to form large flocs, while ordinary water quality has the opposite effect. The pH of pharmaceutical wastewater affects microbial activity, which in turn influences floc formation and stability. The formation and stability of flocs primarily depend on the organic matter in the wastewater, as organic matter serves as an important binding agent for floc formation. High organic matter content enhances stability through binding action. In wastewater management, reducing organic matter content in water bodies improves water structure and enhances floc stability. Water microorganisms play a crucial role in nitrogen transformation and water structure stability. By decomposing organic matter to release nitrogen for plant absorption, they promote floc formation and stability. Maintaining microbial diversity and activity is crucial for improving nitrogen utilization efficiency and water stability. Additionally, annual precipitation, annual evaporation, and annual temperature are significantly correlated with the floc response ratio. However, the use of microbial flocculants in pharmaceutical wastewater treatment does not show a significant correlation with the water response ratio, but there is a trend toward increased response ratios with increasing treatment depth, which contradicts previous research findings. This discrepancy may be due to differences in the selected regions.

IV. Conclusion

This study employs a meta-analysis approach to analyze the water quality characteristics of biological and chemical pharmaceutical wastewater. It investigates the removal efficiency of organic matter and nutrients in wastewater based on flocculant type, and explores the influence of initial pH, total suspended solids (TS) concentration, chemical oxygen demand (COD) concentration, total ammonia nitrogen (TAN) concentration, and total phosphorus (TP) concentration on nutrient removal efficiency when using different flocculants. Pharmaceutical wastewater contains a large amount of difficult-to-degrade organic matter, and it is challenging to achieve compliance with discharge standards using a single method. In practical applications, microbial flocculants must be used in combination with other treatment processes. Flocculants produced by single bacterial strains exhibit relatively low flocculation activity. In practical applications, composite flocculants produced by mixed bacterial strains can be considered for treating pharmaceutical wastewater, while optimizing cultivation conditions to enhance flocculation activity and improve the treatment efficacy of microbial flocculants on pharmaceutical wastewater.

Biological flocculants possess environmental advantages unmatched by inorganic flocculants and synthetic organic flocculants. However, current challenges include high production costs, difficulties in preserving live flocculants, limited functional diversity of flocculants, and challenges in industrial-scale production. Nevertheless, their characteristics and advantages present a promising future for water treatment technology development. Biological flocculants may eventually replace or partially replace traditional inorganic polymers and synthetic organic polymer flocculants. China's research on biological flocculants began relatively late and remains at a relatively low level. In recent years, with the introduction of new technologies, methods, and processes such as mixed microbial culture technology, genetic engineering technology, biological inoculation methods, immobilized biological enhancement technology, and biological fluidized bed technology, the development of biological flocculants has entered a new historical phase. The key breakthrough areas for future research and application of biological flocculants include the following:

(1) Continue to deeply study the physicochemical properties, distribution patterns of flocculation activity, flocculation mechanisms, flocculation kinetics, and factors influencing flocculation of biological flocculants to further establish the theoretical foundation of biological flocculation.

(2) Identify new species, particularly those thriving under extreme conditions, and breed high-yield, high-efficiency strains.

(3) Utilize protoplast fusion and genetic engineering technologies to “create” high-yield, high-efficiency engineered strains, especially by introducing pollutant-degrading plasmids into microbial strains, thereby integrating flocculation, sedimentation, and degradation functions into a single strain and expanding the application scope of flocculants. The U.S. Bio-Bacterial Control Systems Company has extracted biological flocculants capable of releasing hormones from higher algae and reed flowers, which have shown excellent performance in domestic wastewater treatment. Chinese researchers have also attempted to load substances that promote microbial growth, such as enzymes or hormones, onto conventional flocculants to achieve an organic integration of flocculation and biochemical treatment. This aims to shorten the startup time of series systems and the retention time of wastewater in series systems while ensuring effluent water quality, thereby expanding the scope of biological flocculant research to a broader conceptual framework.

(4) Identify inexpensive carbon and nitrogen sources, optimize cultivation conditions, and reduce production costs. This is the key factor determining whether biological flocculants can be industrialized.

(5) Develop new technologies and processes suitable for the research, development, and application of biological flocculants.

(6) Explore the combined use of biological flocculants with inorganic flocculants and organic polymer flocculants to achieve complementary advantages among various flocculants and achieve the goals of enhanced efficiency and energy savings.

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