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One-Way Analysis and Correlation Analysis of Design Parameter's Influence on the Work Condition of Vermifilter

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Abstract

Vermifilter, based on earthworm-microorganism synergistic action, could simultaneously achieve the reduction and stabilization of excess sludge environment-friendly. To make vermifilter work more efficiently and steadily, the diameter of ceramsite, filter height, and influent concentration were investigated in this study. The results showed that though larger ceramicite may decrease the rate of suspended solids (SS) reduction and volatile suspended solids (VSS) reduction slightly, it can improve the ventilation and cooperation of earthworms and microbes, reduce the filter's maximum sludge capability, make the sludge distribution inside the filter be more reasonable and beneficial to the long-term stable operation of the filter. The higher filter could not only bring out a better environment for earthworms and microbes but also enhance the filter's capacity for sludge reduction and stabilization. Nevertheless, higher filters could bring out an extra burden on the infrastructure fee, along with the decrease in the organic loading and the handling capacity of filters. The finding provides a quantitative insight into how the design parameters influence sewage sludge reduction and stabilization in a vermifiltration system.

Subject Areas

Sustainable Wastewater Treatment

Keywords

Vermifilter, Excess Sludge, One-Way Analysis, Correlation Analysis, Filter Height, Diameter of Ceramicists

1. Introduction

Chinese rapid economic development has been amazing around the world in recent years, at an average rate of 6.9% of GDP growth, especially in the field of urbanization (Jin *et al.*, 2014) [1]. Nevertheless, serious environmental problems were caused by the model of inefficient and blind development. The over-speed urbanization results in increasing pressure both on energy consumption and the natural environment. Thus, the large amount of waste discharged during urbanization, along with the prospective strict rules on pollutant discharge, must lead to increasing pressure on the wastewater treatment plants (WWTPs) (Xing *et al.*, 2014) [2], then the excess sludge disposal. It was reported that Sewage sludge treatment and disposal cost approximately 30% - 60% of the total wastewater treatment expenses (Chen *et al.*, 2012 [3]; Murray *et al.*, 2008 [4]).

Most WWTPs in the small towns of China could not afford the huge expenses of the conventional sludge treatment process, such as anaerobic and aerobic digestion. Therefore, it is considerably essential to develop a cost-effective and environmentally friendly method for excess sludge treatment and disposal. Vermifiltration provides an alternative way to treat liquid-state sludge before dewatering, which has turned out to be an ecologically sound, economically viable, and socially acceptable method for small and mid-scale WWTPs.

The vermifiltration has been defined as an ecological technology for municipal sewage treatment since the 1970s (Elvira *et al.*, 1998) [5]. It is well-accepted that the earthworm-microorganism interactions in the vermifilter reactor could enhance the stabilization of excess sludge (Yang *et al.*, 2013 [6]; Zhao *et al.*, 2010 [7]), and the earthworms play an important role as the crucial driving forces in the vermifiltration (Liu *et al.*, 2012) [8]. Researchers have reported that the ingestion of earthworms enables to conversion of different types of organic wastes (domestic as well as industrial) into value-added material (Garg *et al.*, 2006) [9]. The operating principle of vermifilter is to extend the food chain to degrade the energy and nitrogen in the sludge, then realize the goal of bio-solid reduction and stabilization (Wang *et al.*, 2013) [10]. Besides, the increase in microbial community diversity caused by earthworms should not be ignored (Gupta and Garg, 2009) [11]. The vermifiltration shows fantastic advantages in lower construction cost and is more ecologically friendly compared to other sludge treatment technology such as ultrasonic, thermal, and ozone pre-treatment (Sinha *et al.*, 2008 [12]; Wei *et al.*, 2003 [13]).

A large quantity of studies has been conducted on the filter's performance influenced by individual factors, such as types of fillings and filter height. Most of the researchers have not studied in detail the effect of design parameters on vermifiltration (Kumar *et al.*, 2014) [14]. However, as an ecological technology worth popularizing, more attention should be paid to the complex effect in engineering and find out the important one. Consequently, this study aims to investigate the influence of various design parameters on the verifier's working condition to achieve specific research objectives, in the hope of revealing the correlation between parameters and then recommending several practical models for reference.

2. Material and Methods

2.1. Selecting a Template

The experimental setup for vermifiltration is illustrated in **Figure 1**, providing a visual representation of the key components and processes involved in the study. This diagram serves as a valuable guide to understanding the experimental procedure.

The experimental process flow is depicted in **Figure 1**. In the homogenized tank, the excess sludge from the WWTP (characteristics listed in **Table 1**) was diluted to an appropriate concentration by the supernatant of the sedimentation tank. Then the dilution was pumped into a distributing cone, and a few light, hollow, polypropylene plastic balls were used as the fillings, to ensure the influent evenly entered the filter and avoid direct hydraulic impact to the microbes and earthworms. The main treatment process occurred in a thin cylinder, 20 - 30 cm in diameter, 50 - 150 cm in depth, which was filled with oval ceramic pellets and earthworms. Treated by the cooperation of earthworms and microbes, the sludge flowed into the sedimentation tank below. Another cone shape was used to separate the supernatant and substrate, each for recycling or further treatment.

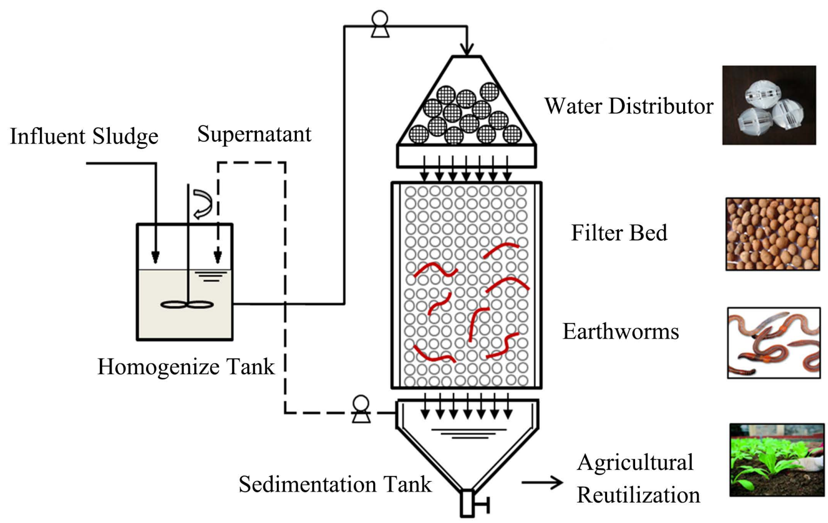


Figure 1. Diagram of the vermifiltration setup in the experiment.

Table 1. Characters of the influent sludge.

Item	Moisture proportion (%)	Volatilization proportion (%)	pH	TCOD (mg/L)	TSS (mg/L)	VSS/SS (%)
Range of value	99.1 - 99.5	54.8 - 82.3	6.8 - 7.3	4200 - 9000	4000 - 7500	52.1 - 82.9

2.2. Experiment Design

Five sets of cylindrical filters were established. Each reactor was added to earthworms at a density of about 32 g/L (Zhao *et al.*, 2010) [7]. *E. fetida* was chosen because it has been shown to process organic wastes with the greatest efficiency (Edwards and Bater, 1992) [15] and it is widely used in vermifiltration technology (Taylor *et al.*, 2003) [16]. The hydraulic load of the reactors was maintained at 4 $m^3/(m^2 \cdot d)$. The working conditions of the five reactors are listed in **Table 2**.

2.2.1. Test of the Filter Height

The height of the filter is referred to as the height of the filling effective height. A higher filter, with a longer Hydraulic Retention Time (HRT), could make the sludge better used by the earthworms and microbes along the depth, while at a cost of low organic loading. Referring to the earlier research, two vermifilters was designed at a different height (50 cm and 80 cm) to study how the factor heights influence the efficiency of the filter. Other parameters are listed in **Table 2**, which are R3 and R4.

2.2.2. Test of the Filling Diameter

Different diameters of the fillings lead to the change of the specific area and porosity. Larger porosity could improve the adsorptive capacity of the fillings, and for more microbes to adhere, which enhance the removal efficiency of the whole filter. However, high level of the specific area causes less porosity. Neither is this good for the inner aeration, nor for shuttle or burrowing of earthworms. Moreover, the filter will block up and break down finally. Then we carefully chose 2 types of pellets ranging in 6 - 9 mm, 6 - 13 mm, with consideration above. Other details are also listed in **Table 2** of R1 and R4.

2.3. Stabilization of the Sludge by Filters

The suspended solids (SS) and volatile suspended solids (VSS) in the influent and effluent were determined by the gravimetric method (China, 2002) [17]. The value of VSS/SS was used to indicate the degree of the sludge stabilization. The less the value gets, the less organism is left in the sludge. The VSS/SS was calculated as follows.

Table 2. Working conditions of the vermifilters.

Code	Filter height (cm)	Filling diameter (mm)	Influent concentration (mg·SS/L)	Organic loading (kgVSS/($m^3 \cdot d$))	Hydraulic loading ($m^3/(m^2 \cdot d)$)	Earthworms density (g/L)
R1	50	6 - 9	300	1.68	4.0	32
R2	50	6 - 13	300	1.68	4.0	32
R3	50	10 - 13	400	2.24	4.0	32
R4	80	10 - 13	400	1.40	4.0	32
R5	150	15 - 20	550	1.03	4.0	32

$$\frac{\text{VSS}}{\text{SS}}(\%)=\frac{S_1-S_2}{S_1}\times 100\% \quad (1)$$

2.4. Statistical Analyses

One-way analysis of variance (ANOVA) was used to identify how the factors (height and diameter) affect the running status of the vermifilters by SPSS V19.0. Correlation analysis of multiple factors was used to study the effect of factors on the filters, also using SPSS V19.0.

3. Result and Discussion

The operation conditions are basic factors in optimally designing the vermifilter. However, the complex correlation among them makes it hard to sort out the clear causality of each parameter. Therefore, one-way and correlation variance analysis were followed to figure out the problem, after the working condition of each experimental part was detailed analyzed.

3.1. Working Conditions in Each Experimental Part

3.1.1. Reduction and Stabilization of the Sludge

The influence of these settings on the filters is shown in Figure 2. Generally, volatile suspended solid (VSS) reduction is used as an indicator of the efficiency of bioreactors on sludge stabilization treatment (Otero *et al.*, 2002) [18]. In the test of the height, the reactors R3 and R4, which adopted larger pellets (10 - 13 mm in diameter), could operate well under the hydraulic loading of 4 $m^3/(m^2 \cdot d)$, and the influent concentration of 400 mg/L. Moreover, the VSS reduction of R4 (higher one) is 25.3% higher than that of R3, while considerably less removal capability (25.7% less than R3) was also observed.

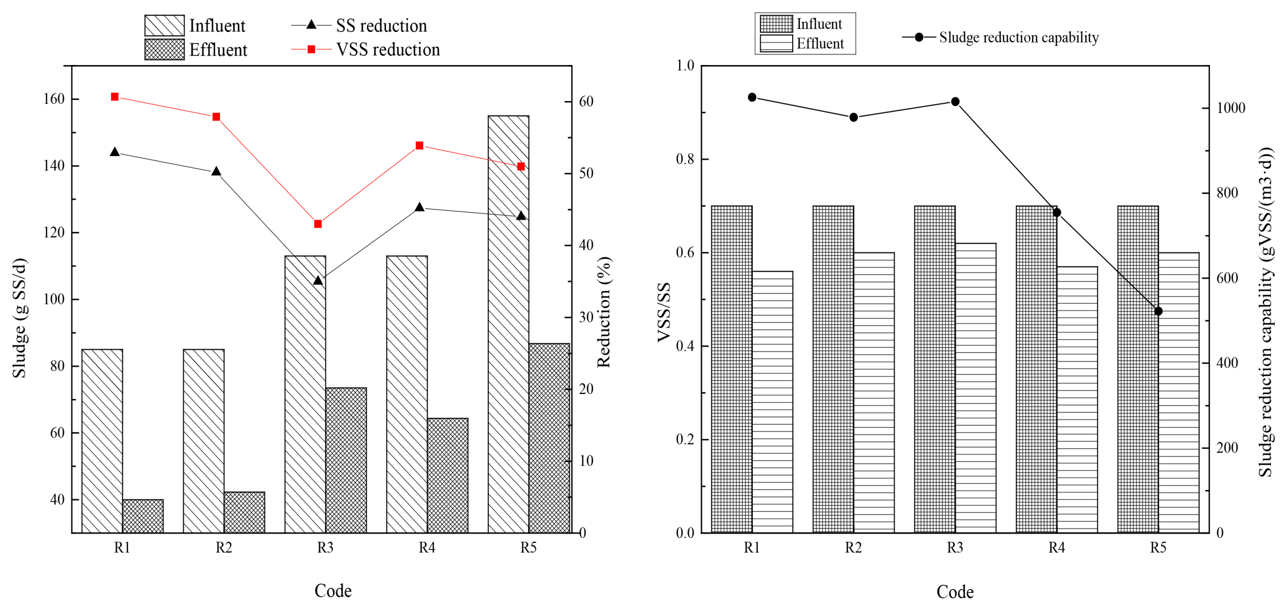


Figure 2. Different removal performance of the filters in corresponding experimental units.

From the test of fillings diameter, we can find that the reactor R1 (6 - 9 mm diameter of the ceramics) reached 52.9% and 60.7% in the SS and VSS reduction, indicating a good state. Yet the influent concentration and quantity of sludge was not so satisfying, about 300 mg/L and 85 g SS/d. As we all know, the influent concentration and quantity of the sludge means this technology whether feasible or not in practice. Besides, the statistics suggested that the larger the diameter was, the less the SS and VSS reduction dropped. Also, the filter with bigger ceramics performed worse in the aspect of the sludge reduction capability. We can primarily conclude that the diameter of the fillings in the filter remarkably influences the operation performance.

3.1.2. Record of the Earthworm Growth

The density and average weight of the earthworms on the filter bed are basic indicators of the earthworm's adaptive status in the filter (Liu *et al*., 2012) [8]. The average weight, density of the earthworms, and the total biomass are listed below (**Figure 3**).

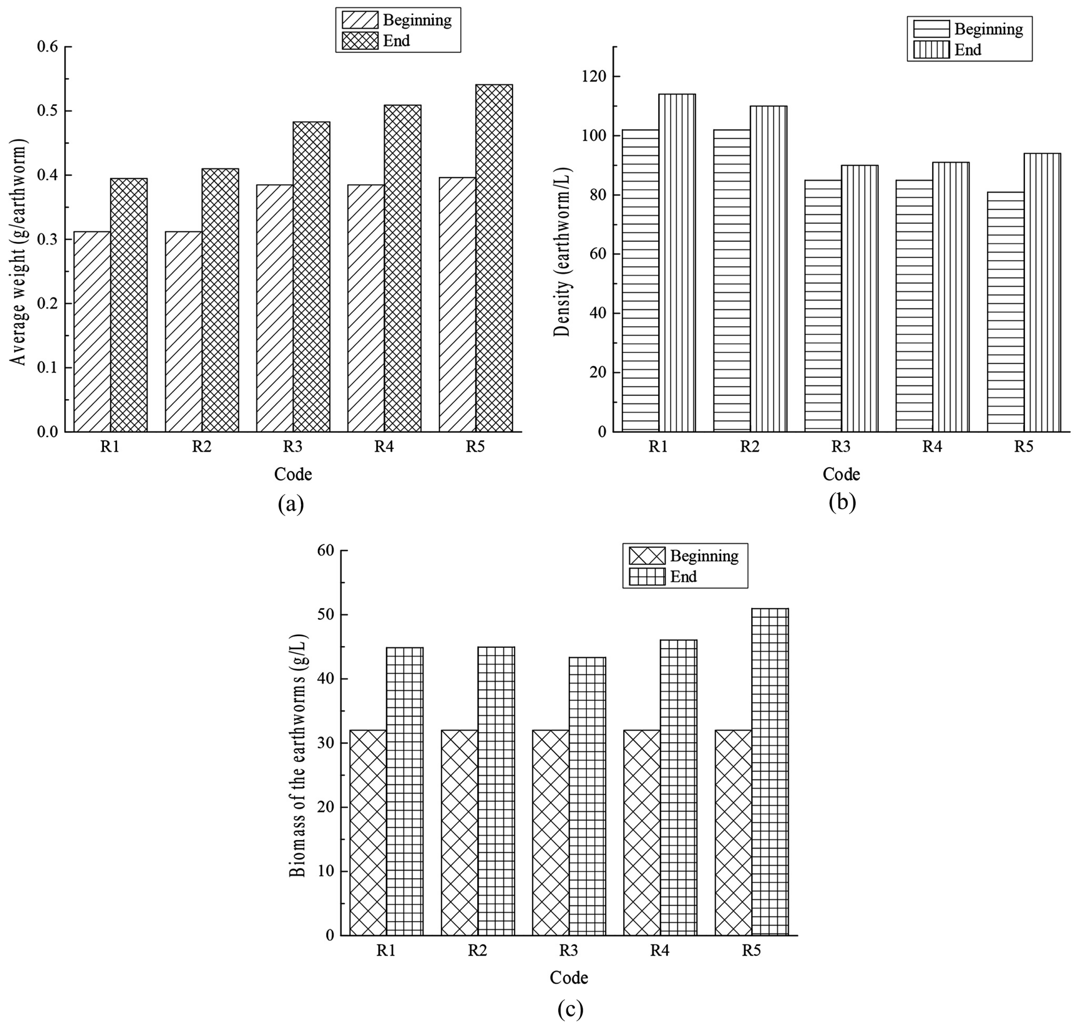


Figure 3. Earthworm's growth in corresponding experimental units.

In this part, during steady operation for 90 days, the average weight and total biomass both increased a bit in every filter. In the test of the diameter of the filling, the average weight of earthworms in reactors R1 and R2 rose at rates of 26.5% and 31.4% respectively. R2 shows a slight advantage against R1 in this part. A similar situation appears in the contrast of R3 and R4 (25.6% and 32.2%). Besides, a 35.6% and 44.1% increase is found in terms of the total biomass of worms in R3 and R4. Primary conduction could be concluded that earthworms in higher reactors show better growth. Summarized then, the weight and biomass of earthworms could be raised on the heels of the increase of filling diameter and filter height.

3.1.3. The Sludge Capability of Each Filter

The earthworms in the vermifilter feed on the organic-rich sludge, making a good contribution to cleaning and digesting the sludge which is intercepted by the haycites (Curry and Schmidt, 2007) [19]. So, the sludge capability was chosen to represent the working condition of both filters and earthworms. Items are shown below (**Figure 4**).

During the steady-state operation, the intercepted sludge in the reactors R1 and R2 remained relatively stable, at the level of 336.29 and 355.25 g SS. The results also showed that the maximum amount of holding sludge in reactor R2 which was filled with a larger diameter of ceramicites reduced by 21.6% than that in reactor R1. During the height test, the average amount of sludge capability was 7.83 and 5.54 g SS/L fillings each in R3 and R4, compared to a total of 276.52 g SS and 312.9 g SS. The discrepancy indicates that the sludge capability per filter volume was higher in the low reactor, while the amount of intercepted sludge dropped. Much more sludge intercepted by a higher reactor could provide more food and a better habitat, which is one of the reasons to explain the better earthworm growth in **Figure 2**.

The long-term monitoring of the sludge capability of filters with different design parameters suggested that each parameter concerned could directly influence the important monitoring index. The significance of this experiment lies in

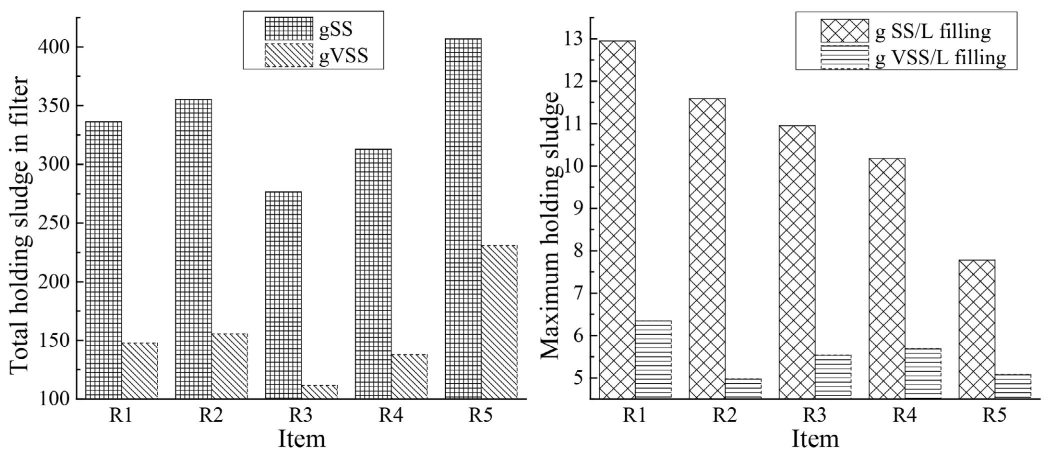


Figure 4. Different sludge capabilities of the filters in corresponding experimental units.

that when we properly adjust these parameters, such as the height and diameter of the fillings, not only the total and maximum sludge capability could be controlled correspondingly, but also the influent SS, the daily treatment capacity of this technology could be improved. It's also what we seek during popularizing the ecological treatment process.

3.2. Statistical Analysis of the Impact of the Design Parameters on the Filter's Working Condition

3.2.1. One-Way Analysis of Variance of the Parameters to the Filter Performance

The factor analysis approach is a statistical method used to calculate and identify how the factors (internal variables) influence those omnibus indexes. This special approach is adopted here to evaluate the impact of those parameters on the filter's condition, and more improvement will be raised later. Then, the removal efficiency, earthworm growth, and sludge capability will be analyzed separately, corresponding with the design indexes: filter height and diameter of ceramists.

1) Diameter of ceramicites

As we all know, there is close relativity among the filling diameter, specific surface area, and filter porosity. The larger the fillings are, the smaller the specific surface will be, and then the larger porosity appears. All these physical characteristics will affect the microbes adhered to the ceramicites, then the overall efficacy of the filter. Listed below in **Table 3** are the analysis results. As the ceramicites of R2 were designed larger than R1, the filter's performance of sludge stabilization got a bit worse. Nevertheless, the filter with larger ceramicists (R2) shows better performance in the aspect of earthworm weight and filter's maximum sludge capability.

Compared to the SS and VSS reduction of the filters, reactor R2 with larger ceramicites performed worse treatment efficiency than reactor R1. However, they both meet the rules set in the discharge standard of pollutants for municipal

Table 3. The influence of the filling diameter on the filter's working efficiency.

Item	SS Reduction (%)	VSS Reduction (%)	Growth rate of earthworm weight (%)	Increase rate of earthworm density (%)	Increase rate of earthworm biomass (%)	Filter's maximum sludge capability (g/L)
R1	52.87	60.60	26.47	11.67	40.45	12.95
R2	50.23	57.91	31.41	7.55	40.55	11.59
Variation ratio	−4.99%	−4.58%	18.64%	−35.29%	0.25%	−10.50%
Effect	↓	↓	↑	↓	-	↑

↑ means the factors have some positive influence on the vermifilter's function; ↓ means the factors have some negative influence on the vermifilter's function; - means the factors have no obvious influence on the vermifilter's function.

wastewater treatment plants in China (China, 2002) [20]: All sludge treatment processes (anaerobic and aerobic digestion) must degrade more than 40% of the VSS in the sludge. Therefore, the influence of the diameter of the filling seems not so attractive to the treatment efficiency.

Earthworms prefer sludge rich in organic matter, so larger fillings could enhance the influent concentration as well as the filter's unit area capacity. Besides, the abundant organic matter like protein, amylose, fat, and inorganic elements like Nitrogen, Phosphorus, and Potassium provide a valuable food source for earthworms (Suthar, 2009) [21]. The close comparison reveals that the quantity of earthworms increased at a slower pace than the weight. A reasonable explanation for this phenomenon is that earthworms could accommodate their community density to the surrounding environment. From our point, the earthworm density is expected to be maintained at a high level, so the worm's ingestion and digestion of the excess sludge could be fully excavated. Going too far is not yet a good solution. The over-dense community of earthworms could cause a series of unhealthy effects: too many worms compared to the ceramicists lead to a lot of limits like narrow dwelling, less food and oxygen distributed, and then the excessive accumulation of metabolic waste, and finally the aggravating competition results in the much lower prolificacy (Kumar *et al.*, 2014 [14]; Li *et al.*, 2008 [22]).

Analysis in this unit also shows that there is still much room for improvement in the growth of earthworm weight and biomass, compared to the number of earthworms. To sum up, high porosity stacked by larger ceramicists strengthens the positive function of earthworms, which not only provides better ventilation for earthworms to discharge their waste out of filters but also avoids the continuous accumulation of excessive sludge and microbes in conventional filters.

2) Height of filters

The influence of height variation on the filter's working effect is shown in Table 4. The rise of the filter height brought an overall promotion of the filter's cumulated 7.03% less sludge than the 50 cm one. More attention should be paid

Table 4. The influence of the filter height on the filter's working efficiency.

Item	SS Reduction (%)	VSS Reduction (%)	Growth rate of earthworm weight (%)	Increase rate of earthworm density (%)	Increase rate of earthworm biomass (%)	Filter's maximum sludge capability (g/L)
R3	34.95	43.01	25.56	5.65	35.65	10.95
R4	45.21	53.89	32.21	6.59	44.11	10.18
Variation ratio	29.36%	25.30%	25.78%	17.86%	23.53%	−7.03%
Effect	↑	↑	↑	↑	↑	↑

↑ means the factors have some positive influence on the vermifilter's function.

efficiency. Especially, the maximum sludge capability in 80 cm height filters ac to this index because it's key to judge whether the filter working in a stable condition or not. Other messages can also be reflected from it: the foraging and growing condition of earthworms, and the distribution of the sludge in the filter. The accumulative efficacy of these indexes comes up to a degree of more than 60% compared to the lower filter, which is impressive.

There is still one point worth mentioning, the higher filter could bring out some burden on the infrastructure fee, along with the decrease in the organic loading and the handling capacity of filters. Therefore, it is very important and challenging to take the working efficiency and construction costs into consideration.

3.2.2. Multiple-Factor Analysis of the Design Parameters' Influence on to Filter's Performance

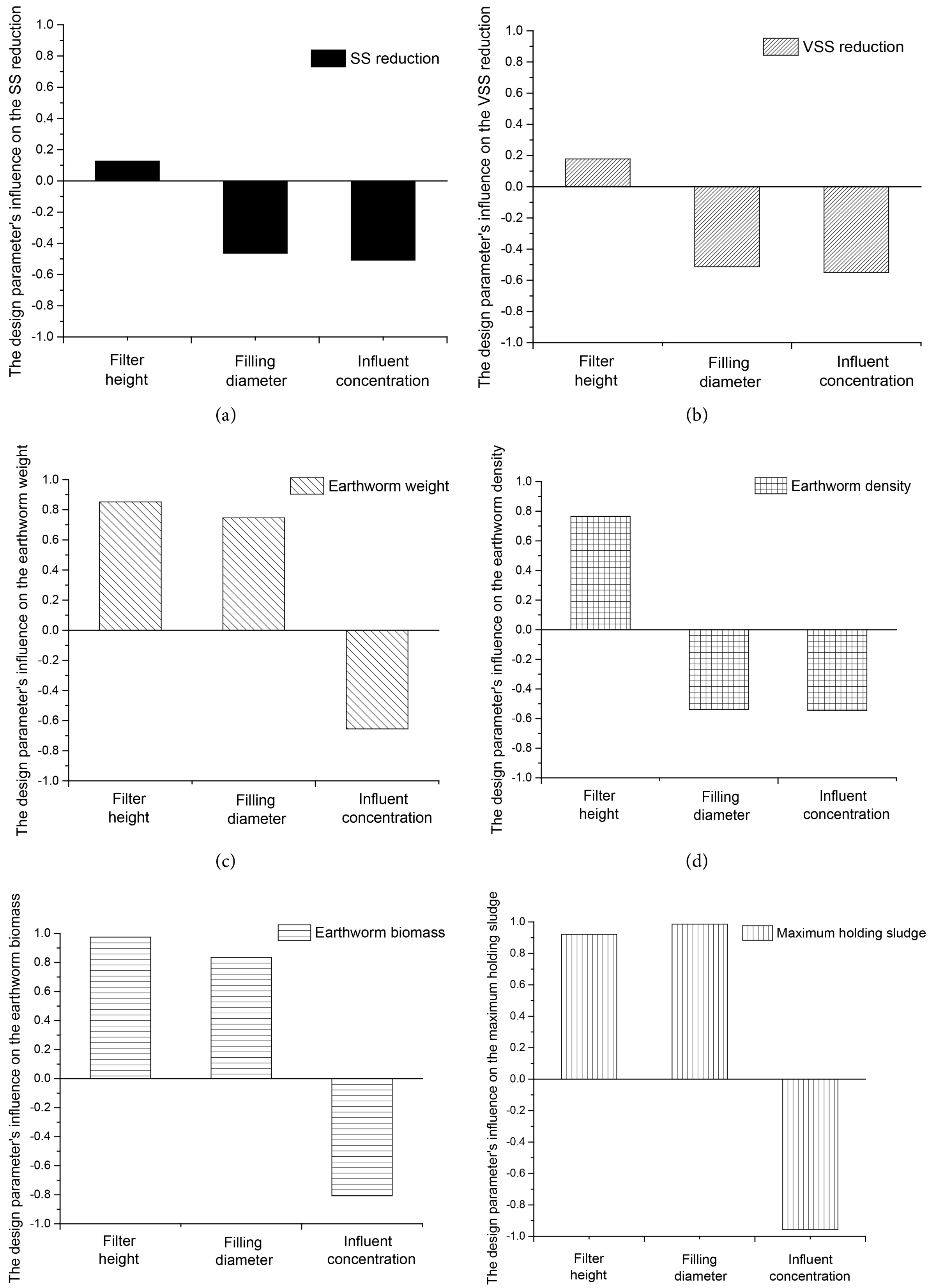
In this part, correlation analysis is used to study the relation between three design parameters, and with the six representative indexes of the filter's condition, to find the key ones and set models worth reference. The results of the correlation analysis of the influence between design parameters and the filter's working condition are shown in **Table 5** and **Figure 5**. Judging from the filter's performance on sludge reduction and stabilization, the design parameters ceramicites diameter and influent concentration could markedly influence the SS and VSS reduction, which is also a confirmation of the previous conclusion about the importance of filling diameter. Moreover, influent concentration shows a slight advantage towards the diameter of the influence.

The foregoing discussion has confirmed that larger porosity of fillings could bring about many benefits such as improvement of the sludge distribution inside the filter, smoother discharge of the earthworm casts, fresh and plenty of food, oxygen for all the living things, and finally, the treatment effect would be strengthened. Similarly in this part, improvement of the insider environment of the

Table 5. Correlation analysis of the influence between design parameters and the filter's working condition.

Item	SS Reduction (%)	VSS Reduction (%)	Growth rate of earthworm weight (%)	Increase rate of earthworm density (%)	Increase rate of earthworm biomass (%)	Filter's maximum sludge capability (g/L)
Filter height	0.127	0.178	0.852	0.765	0.975**	0.921*
Filling diameter	−0.464	−0.513	0.746	−0.538	0.835	0.986**
Influent concentration	−0.508	−0.550	−0.655	−0.546	−0.807	−0.957*

*means significant correlation at 0.05 level; **means excellent correlation at a 0.01 level.



(a) (b) (c) (d) (e) (f)

Figure 5. The design parameter's influence on the filter's working condition.

filter would strongly affect the earthworm condition, especially the growth of weight and biomass. Combining statistics in **Table 5** with graphs (c), (d), and (e), an excellent correlation is found between the filter height and growth rate of earthworm biomass. A reasonable explanation is that by increasing the filter height by packing separate parts, the filter's ventilation area and inside ventilation are both enhanced, positive effect works on the above-mentioned indexes accordingly.

The maximum amount of holding sludge is quite essential index to reflect the reactor's stability and monitor it whether blocks or not. Detailed analysis from the statistics and graph suggests all the design parameters present markedly correlated with the filter's maximum sludge capability, among which the ceramicite diameter appears to be excellently related ($p < 0.01$). This result demonstrates the significance of the filling diameter once again. Therefore, the type and size of the fillings must be taken into close consideration at the beginning of the filter design and construction.

4. Conclusions

In conclusion, this study conducted a series of specific experiments to investigate the impact of various design parameters on the filter's working performance. The analysis, which employed two analytical methods, revealed valuable insights into the internal relationships among these parameters. The following key findings and suggestions can be drawn from this research:

1) For the vermifilter, though larger ceramicists may decrease the rate of SS reduction and VSS reduction slightly, it can improve the ventilation and cooperation of earthworms and microbes, reduce the filter's maximum sludge capability, make the sludge distribution inside the filter be more reasonable and is beneficial to the long-term stable operation of the filter. Meanwhile, compared with the filter height, the diameter of the fillings presents a more remarkable correlation with the filter's performance.

2) A higher filter could not only bring out a better environment for earthworms and microbes but also enhance the filter's capacity for sludge reduction and stabilization, which is just needed in practical engineering. Nevertheless, higher filters could bring out an extra burden on the infrastructure fee, along with the decrease in the organic loading and the handling capacity of filters. Therefore, it's significant to find a balance between working efficiency and construct cost.

3) Utilizing multiple adjustments and repetition, a series of models for practical reference is summarized: at the hydraulic load of 4 $m^3/(m^2 \cdot d)$, vermifiters with ceramicists ranged in 6 - 9, 10 - 13, 15 - 20 in diameter could deal with the excess sludge at around 300, 400, 600 mg SS/L correspondingly, and they would realize a steady-state condition to discharge effluent sludge on a standard level.

Conflicts of Interest

The authors declare no conflicts of interest.

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