Digested Slurry Analysis for Utilization Based on Irrigated Crop Water Demand

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To rationally utilize digested slurry, and thereby promote the integrated development of planting and breeding in breeding industry, the water-fertilizer requirement analysis of typical winter wheat-summer corn rotation tillage model in Zhengzhou was completed based on the water/nutrient requirement of crops. The results showed that the water demand and effective rainfall of winter wheat during the whole growth period were 492 and 190 mm, and the application amount of digested slurry was 3090 m³. The N, P, and K provided were 3600, 197, and 1310 kg, respectively, which exceeded the normal nutrient requirement of wheat. During the whole growth period of summer corn, the water demand was 354 mm, the effective rainfall was 290 mm, and the application amount of digested slurry was 763 m³. The amount of N, P, and K provided was 890, 48.6, and 324 kg, respectively. The amount of N and K exceeded the normal nutrient demand of corn, while the P was insufficient. Therefore, digested slurry can provide full nutrient requirements in winter wheat planting season in Zhengzhou, and P fertilizer should be added when applying digested slurry in corn planting season. If long-term application, excessive nutrient loss may cause non-point source pollution.

DOI: 10.15376/biores.18.4.7098-7108

Keywords: Crop water demand; Digested slurry; Water-fertilizer; Nutrients

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INTRODUCTION

In recent years, with the increase of people’s demand for meat, eggs, and milk, the number of livestock and poultry breeding enterprises is gradually increasing, and the scale of breeding is gradually expanding. The rapid development of large-scale and intensive farming mode has realized the maximum utilization of confined space, but a large breeding density will produce a large amount of fecal contamination, which may cause the rapid spread of fungi and viruses if not treated in time. At present, the resource utilization of livestock and poultry manure mainly includes aerobic compost, processed feed, anaerobic fermentation, and so on (Li et al. 2020; Liu et al. 2021a). Anaerobic fermentation can decompose organic matter in manure, and the biogas, digested slurry, and digested sludge produced can also be used, so it is widely used in aquaculture as an effective way to treat manure.

As the main way to treat aquaculture sewage and reduce agricultural pollution, biogas fermentation can effectively remove organic matter in aquaculture sewage (Köthe et al. 2020; Zhu et al. 2021; Qu et al. 2022; Zhu et al. 2022), but the content of organic matter in discharged digested slurry is still high (Deng et al. 2014; Yan et al. 2019; Wang...
et al. 2020; Liu et al. 2021b), and direct discharge can easily cause secondary pollution (Li et al. 2017a). Digested slurry is rich in nutrient elements, including nitrogen, phosphorus, potassium, zinc, iron, as well as trace elements and organic matter (Li et al. 2017b; Ke et al. 2022). These substances can be used by plants for growth and development, the application can be quick and efficient, and the nutrients can easily be absorbed (Cao et al. 2016; Liu et al. 2022; Zhang et al. 2022). Also, the nutrients have a high utilization efficiency (Wu et al. 2013). Thus, digested slurry fertilizer is currently the main way to use the slurry.

Digested slurry can be used as a kind of high-quality organic fertilizer for crop planting after treatment. Reasonable application not only can improve the rural environment, but it also can realize the purpose of turning waste into value. Studies have found that applying digested slurry water and fertilizer can effectively increase the content of soil organic matter (Yan et al. 2019; Tang et al. 2022) and available nutrients (You et al. 2019; Yu et al. 2022). Some studies suggest that application of digested slurry fertilizer can increase the number of bacteria, fungi, and actinomycetes in soil (Wentzel and Joergensen 2016; Tang et al. 2021) and thereby improve the soil’s micro-ecological environment (Wang et al. 2023). Studies have also shown that the application of digested slurry water and fertilizer has significant effects on improving crop quality and increasing yield (Tang et al. 2019; Ai et al. 2020; de França et al. 2021; Tang et al. 2022), improving soil structure (Du et al. 2016; Xu et al. 2019), and reducing pests and diseases (Westphal et al. 2016).

At present, the application of digested slurry as water and fertilizer usually follows the principle of nutrient balance. Studies have shown that applying digested slurry according to the nutrient requirements of rice at different growth stages can increase crop yield 3.2% to 8.7% (Luo et al. 2022). However, for dryland crops, although this digested slurry application model can meet the nutritional requirements of crops, its water supply is often less than the crop water demand, so additional irrigation may be needed to meet the crop water demand. Combined with the distribution of rainfall time and the water/nutrient requirements at different growth stages of crops, a scientific application model of digested slurry water and fertilizer based on water balance and supplemented by nutrient balance was established, which could better solve the problem of insufficient water supply to crops in the application process of digested slurry. To provide scientific reference for rational utilization of digested slurry to promote the combined development of breeding industry, this study analyzed the water and fertilizer requirements of typical winter wheat-summer corn rotation tillage mode in Zhengzhou, using the water/nutrient requirements of crops as indexes.

MATERIAL AND METHODS

Zhengzhou is located in the central and northern part of Henan Province (China), situated in the Huanghuaihai Plain. The geographical location is 112°42' to 114°14'N and 34°16' to 34°58'E, the total area is 7567 km², the plain area accounts for approximately 38.4%, and the main planting system of the plain area is winter wheat and summer corn, two crops a year. The study area is a semi-arid and semi-humid warm temperate continental monsoon climate area, with significant seasonal climate changes and uneven rainfall distribution. The average annual temperature is 14.7 °C, with the lowest average temperature of 0.5 °C in January and the highest temperature of 27.1 °C in July. The
average annual rainfall is 632.40 mm, mainly from June to August, with the most falling in August.

Crop water demand was calculated according to the crop coefficient method proposed by the Food and Agriculture Organization of the United Nations (FAO). The formula used for calculation is shown in Eq. 1,

$$ E_{pi} = ET_{oi} \times K_{ci} \quad (1) $$

where $E_{pi}$ is the evapo-transpiration of crops in a certain growth period (mm); $ET_{oi}$ is the potential evapo-transpiration (mm) during the growth period; and $K_{ci}$ is the crop coefficient of this growth period.

The potential evapo-transpiration $ET_0$ of crops was calculated using the MHS-2 formula. The formula used for calculation is,

$$ ET_0 = \left[ 0.00193 R_a (T_{ave} + 17.8)(T_{max} - T_{min})^{0.517} \right] / \lambda \quad (2) $$

where $ET_0$ is the reference crop evapo-transpiration (mm); $R_a$ is extra-atmospheric solar radiation (MJ·m$^{-2}$·d$^{-1}$); $T_{ave}$ is the average temperature (°C); $T_{max}$ and $T_{min}$ are the highest and lowest temperature, respectively (°C); and $\lambda$ is the latent heat of water gasification ($\lambda = 2.45$ MJ·kg$^{-1}$).

The part of natural precipitation that can be directly or indirectly utilized by crops is the effective rainfall, which can be calculated according to the effective utilization coefficient method. The calculation formula is given as Eq. 3:

$$ P_{ej} = \alpha_j \times P_j \quad (3) $$

In Eq. 3, $P_j$ is the total rainfall (mm); and $\alpha_j$ is the effective utilization coefficient of rainfall. The values of $\alpha$ are as follows: when $P_j \leq 5$ mm, $\alpha_j = 1$; When $5 \text{ mm} < P_j \leq 50$ mm, $\alpha_j = 0.9$; $P_j > 50$ mm, $\alpha_j = 0.75$.

The effective rainfall of a certain growth period is the sum of the effective rainfall in the period, and the formula is Eq. 4,

$$ P_{ei} = \sum_{j=1}^{n} P_{ej,i} \quad (4) $$

where $P_{ei}$ is the effective rainfall of growth stage $i$ (mm); $j$ is the number of rainfall in the growth period; and $P_{ej,i}$ is the effective rainfall of the $j^{th}$ rainfall in growth stage $i$ (mm).

The application rate of digested slurry was the difference between the water demand and the effective rainfall at each growth stage. The calculation formula used is Eq. 5,

$$ BS = \begin{cases} ET_C - P_e, & ET_C - P_e > 0 \\ 0, & ET_C - P_e \leq 0 \end{cases} \quad (5) $$

where $BS$ is the application amount of digested slurry water and fertilizer (mm); $ET_C$ is the crop water demand, mm; and $P_e$ is the effective precipitation, mm.

The main nutrient contents (mg/L) of different fermentation substrates digested slurry are shown in Table 1 (Dong et al. 2021).

Applying digested slurry to bring nutrients can be calculated according to the amount of digested slurry application and digested slurry nutrient content. The formula used for calculation is shown in Eq. 6,

$$ N + P + K = W \cdot (\beta_N + \beta_P + \beta_K) \quad (6) $$
where $N$, $P$, and $K$ are the total amount of nitrogen, phosphorus, and potassium provided by applying digested slurry, respectively; $W$ is the application amount of digested slurry; and $\beta_N$, $\beta_P$, and $\beta_K$ are the percentages of nutrient contents in applied digested slurry.

**Table 1. Nutrient Content of Different Types of Digested Slurry**

<table>
<thead>
<tr>
<th>Digested Slurry Type</th>
<th>TN (mg/L)</th>
<th>TP (mg/L)</th>
<th>TK (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pig manure digested slurry</td>
<td>1166.71</td>
<td>291.60</td>
<td>1144.26</td>
</tr>
<tr>
<td>Cow dung digested slurry</td>
<td>1488.59</td>
<td>561.67</td>
<td>1679.10</td>
</tr>
<tr>
<td>Chicken manure digested slurry</td>
<td>3226.13</td>
<td>959.71</td>
<td>2858.31</td>
</tr>
<tr>
<td>Household biogas digester digested slurry</td>
<td>1369.31</td>
<td>665.90</td>
<td>1240.21</td>
</tr>
</tbody>
</table>

The analysis of water and fertilizer utilization characteristics of digested slurry mainly involves daily rainfall and maximum and minimum temperature in Zhengzhou from 2016 to 2020 from the website [http://www.agdata.cn/](http://www.agdata.cn/). Microsoft Excel 2021 was used for data analysis, and Microsoft Word 2021 and Origin 2021 were used for chart production.

**RESULTS AND DISCUSSION**

Winter wheat planting occurs generally from mid-October to mid-June of the next year. The whole growth period was 247 days. Summer corn period is from mid-late June to mid-September. The whole growth period was 102 days. The evapo-transpiration of wheat and corn in each growth period was calculated by Eqs. 1 and 2. The results are shown in Tables 2 and 3 (Yang *et al.* 2008).

**Table 2. Water Demand of Wheat at Different Growth Periods**

<table>
<thead>
<tr>
<th>Growth Period</th>
<th>$ET_0$ (mm)</th>
<th>Crop Coefficient</th>
<th>$E_p$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overwintering</td>
<td>91.69</td>
<td>0.6</td>
<td>49.76</td>
</tr>
<tr>
<td>Regreening</td>
<td>93.61</td>
<td>0.7</td>
<td>58.87</td>
</tr>
<tr>
<td>Jointing</td>
<td>105.41</td>
<td>0.9</td>
<td>90.11</td>
</tr>
<tr>
<td>Heading</td>
<td>151.61</td>
<td>1.1</td>
<td>145.89</td>
</tr>
<tr>
<td>Maturity</td>
<td>187.94</td>
<td>0.9</td>
<td>147.06</td>
</tr>
</tbody>
</table>

**Table 3. Water Demand of Corn at Different Growth Periods**

<table>
<thead>
<tr>
<th>Growth Period</th>
<th>$ET_0$ (mm)</th>
<th>Crop Coefficient</th>
<th>$E_p$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jointing</td>
<td>110.97</td>
<td>0.47</td>
<td>43.90</td>
</tr>
<tr>
<td>Tasseling</td>
<td>146.39</td>
<td>0.83</td>
<td>108.07</td>
</tr>
<tr>
<td>Filling</td>
<td>86.12</td>
<td>1.12</td>
<td>89.43</td>
</tr>
<tr>
<td>Maturity</td>
<td>112.63</td>
<td>1.17</td>
<td>112.97</td>
</tr>
</tbody>
</table>

As shown in Tables 2 and 3, the water demand intensity of winter wheat in different growth stages changed significantly, as shown by the following: The water demand increased gradually from 49.8 mm during sowing-overwintering stage to 147 mm during peak heading to maturity stage, and the total evapo-transpiration during the whole growth stage was 492 mm.
The water demand intensity of summer corn fluctuated greatly during the whole growth period, as follows: the water demand increased from sowing to jointing to jointing to tasseling, and then decreased. The water demand increased again during growth to maturity and reached the maximum value of 113 mm, and the total evapo-transpiration during the whole growth period was 354 mm.

The effective rainfall $P_e$ at various growth stages of wheat and corn was calculated by Eqs. 3 and 4, and the application amount $BS$ (mm) of digested slurry was calculated by Eq. 5, taking pig manure as an example, as shown in Table 3. The contribution of rainfall and digested slurry to crop water demand is shown in Fig. 1.

![Fig. 1. Contribution ratio of rainfall and digested slurry to water demand at different growth stages of crops](image)

**Table 4. Effective Rainfall and Application Amount of Digested Slurry at Different Growth Stages of Wheat**

<table>
<thead>
<tr>
<th>Growth Period</th>
<th>$P_e$ (mm)</th>
<th>$BS$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overwintering</td>
<td>56.59</td>
<td>0</td>
</tr>
<tr>
<td>Regreening</td>
<td>26.53</td>
<td>32.34</td>
</tr>
<tr>
<td>Jointing</td>
<td>7.48</td>
<td>82.62</td>
</tr>
<tr>
<td>Heading</td>
<td>29.43</td>
<td>116.46</td>
</tr>
<tr>
<td>Maturity</td>
<td>69.68</td>
<td>77.38</td>
</tr>
</tbody>
</table>
Table 5. Effective Rainfall and Application Amount of Digested Slurry at Different Growth Stages of Corn

<table>
<thead>
<tr>
<th>Growth Period</th>
<th>$P_e$ (mm)</th>
<th>BS (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jointing</td>
<td>47.45</td>
<td>0</td>
</tr>
<tr>
<td>Tasseling</td>
<td>116.89</td>
<td>0</td>
</tr>
<tr>
<td>Filling</td>
<td>51.39</td>
<td>38.05</td>
</tr>
<tr>
<td>Maturity</td>
<td>74.74</td>
<td>38.22</td>
</tr>
</tbody>
</table>

As shown in Tables 4 and 5, the effective rainfall of wheat season was less, and the effective rainfall of the whole growth period was 190 mm; the effective rainfall of heading to maturity period was the most, 69.7 mm; and the least was 7.48 mm, during the greening to jointing period. There was more effective rainfall in the corn season, 290 mm in the whole growth period, 117 mm in the jointing to tasseling stage, and 47.4 mm in the seeding to jointing stage. The application amounts of digested slurry in wheat and corn during the whole rearing period were 309 and 76.3 mm, respectively, and the application amounts per hectare were 3090 and 763 m³, respectively.

As shown in Fig. 1, the irrigation demand of winter wheat was relatively large. Except for the sowing-overwintering period, digested slurry should be applied as water supplement, accounting for more than 50% and reaching 92% during the greening-jointing period. Compared with wheat, supplementary irrigation was needed only in the tasseling-filling and grain-ripening stages of corn, and the proportion was less than 50%. The reason is that the corn planting season rainfall generally is abundant, while the wheat planting season rainfall is likely to be low, and the water demand is large. During the whole growth period, 3090 m³ of biogas slurry was applied to wheat and 763 m³ of biogas slurry was applied to corn per hectare. Irrigation was carried out at different growth stages according to crop water requirements. The application of biogas slurry provided 3600, 902, and 3530 kg of N, P and K for wheat, and 890, 223, and 873 kg of N, P and K for corn, respectively. Converted to N, P₂O₅, K₂O, then the nutrient supply and demand relationship of wheat and corn is shown in Fig. 2.

As shown in Fig. 2, based on the water balance of digested slurry, the supply of N, P, and K for wheat was greater than the demand, while the P supply for corn was insufficient, and the supply of N and K also appears to have been greater than the demand. Long-term excess of nutrient supply had no obvious effect on the quality and yield improvement of crops in the current season. Crop yield reached the highest level in a certain organic fertilizer application level, and the yield level tended to be stable or declined when the application amount of biogas slurry was further increased (Chang et al. 2010). Some nutrients such as N, P, and K lost with rainwater can easily lead to eutrophication of water bodies, affecting water quality and causing the risk of non-point source pollution. Horizontal long-term balanced application of organic fertilizer can ensure that crop yield and stability are still maintained after short-term reduction or stop application and can increase soil carbon sequestration (Tian et al. 2023).

Scientific application of biogas slurry not only can ensure crop yield and quality, but it also can reduce the risk of environmental pollution. According to the relationship between nutrient supply and demand, the oversupply of N in wheat season and K in corn season is the biggest factor that increases the risk of non-point source pollution. The scientific application dosage of pig manure biogas slurry as the source of nitrogen fertilizer,
phosphate fertilizer, potassium fertilizer, and the minimum pollution risk were calculated, and the results are shown in Table 6.

![Graph showing nutrient supply and demand for wheat and corn](image)

**Fig. 2.** Relationship between nutrient supply and demand of wheat and corn

**Table 6.** Application Amount of Biogas Slurry as a Source of Different Nutrient Elements and the Minimum Risk of Pollution

<table>
<thead>
<tr>
<th>Crop Season</th>
<th>Nitrogenous Fertilizer (m³)</th>
<th>Phosphate Fertilizer (m³)</th>
<th>Potassium Fertilizer (m³)</th>
<th>Minimal Pollution Risk (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat season</td>
<td>153.21</td>
<td>1041.55</td>
<td>486.31</td>
<td>153.21</td>
</tr>
<tr>
<td>Corn season</td>
<td>404.89</td>
<td>2474.26</td>
<td>371.09</td>
<td>371.09</td>
</tr>
</tbody>
</table>

As can be seen from Table 4, when biogas slurry was applied as phosphate fertilizer in wheat season, the maximum amount was 1040 m. At this time, the supply of N and K was still greater than the demand, and the minimum amount was 153 m³ when it is used as nitrogen fertilizer. At this time, the supply of P and K was less than the demand, and the pollution risk was minimal. When corn biogas slurry was used as phosphate fertilizer, the application amount was the largest, i.e. 2470 m, and the supplies of N and K were in excess. When it was used as potassium fertilizer, the amount was the least, and the supply of N and P was less than the demand, and the pollution risk was the least. The application rate of biogas slurry with minimum pollution risk can reduce pollution risk as a scientific application level. In order to ensure crop yield and quality, the corresponding nutrient element fertilizer should be supplemented as needed.
CONCLUSIONS

Based on the analysis of the scientific application mode of digested slurry based on water balance and supplemental nutrient balance in wheat-corn rotation in Zhengzhou, the following conclusions can be drawn:

1. The water demand of winter wheat in the whole growth period of Zhengzhou was 492 mm, the effective rainfall was 190 mm, and the application amount of digested slurry was 309 mm. The overall irrigation demand was large, except for sowing-overwintering period, all needed irrigation, accounting for more than 50%, and the greening-jointing period reached 92%. The water demand of summer corn in the whole growth period was 354 mm, the effective rainfall was 290 mm, and the application amount of digested slurry water and fertilizer was 76.3 mm. The irrigation demand was small, and supplementary irrigation was needed only in the tasseling-grouting and grout-mature stages, and the proportion was less than 50%.

2. N, P, O5, and K2O of digested slurry applied in single rotation per hectare of cultivated land were 3600, 197, and 1310 kg for wheat and 890, 48.6, and 324 kg for corn, respectively. The supply of N, P, and K of wheat was greater than the demand, but the P supply of corn was insufficient, and the supply of N and K was greater than the demand. Long-term oversupply of nutrients had no obvious effect on crop quality and yield improvement. The loss of nutrients is easy to lead to water eutrophication, affecting water quality, and causing the risk of non-point source pollution.

ACKNOWLEDGMENTS

The authors are grateful for the financial support provided by National Key R&D Program of China (2021YFD1700900).

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Article submitted: June 21, 2023; Peer review completed: July 26, 2023; Revised version received and accepted: August 3, 2023; Published: August 23, 2023. DOI: 10.15376/biores.18.4.7098-7108.