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Assessment of Environmental and Social Effects of Rural Toilet Retrofitting on a Regional Scale in China

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In China, more than 47 million toilets in rural areas have been upgraded since the nationwide sanitation program, popularly referred to as the "toilet revolution," was launched in 2015. However, little is currently known about the environmental risks of manure, or rural residents' satisfaction. Here, we have selected 50 rural residents from 10 provinces and focused on two types of toilets to evaluate the environmental and social impacts of improving toilets in rural areas. The monitoring results showed that human excrement was mainly alkaline, and the concentrations of total nitrogen and phosphorus in the composting toilets ranged from 259.21 to 330.46 mg/kg and from 2.71 to 3.71 mg/kg, respectively, while their contents in septic tank effluents were generally 381.31–2040.84 mg/L and 10.41–80.46 mg/L, respectively. The pH and EC values exceeded the soil background value in individual regions, and the harmless effect of the two types of toilets did not fully meet the standard requirements, indicating that toilet manure, albeit possessed certain resource utilization potential, guard against the risk of pollution. Additionally, based on a fuzzy comprehensive evaluation model, it was found that the comprehensive evaluation score of Jiangsu Province is the highest, that of Gansu Province is the lowest, and the overall score is "high in the southeast and low in the northwest." This study provides basic data and references for establishing a scientific and feasible evaluation system of rural toilet retrofitting and strengthens government guidance and training related to toilet retrofitting.

Keywords: toilet reform, harmless effect, manure utilization, comprehensive evaluation, physicochemical

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1 INTRODUCTION

In the process of rapid economic development and the continuous advancement of rural urbanization, the huge population and remote geographical location of rural areas have meant that they have long-term disadvantages in terms of infrastructure, science and technology, and development awareness, especially with regard to rural toilets, which are considered to be the most difficult to manage, and there is a lack of rural infrastructure in developing countries (Cheng et al., 2018; Li et al., 2021). Non-hygienic toilets, such as open toilets, in which feces cannot be safely stored quickly enough, can cause intestinal infectious diseases such as dysentery and typhoid fever, thereby increasing the risk of death from infectious diseases (Chen and Kallawicha, 2021; Gao et al., 2021). Some studies have also indicated that the contributions of total nitrogen and total phosphorus from toilet sewage accounted for 84% of the total pollutant load of rural domestic sewage (Angelakis et al., 2015). Recently, the Chinese government has launched a series of special actions toward the retrofitting of toilets in rural areas and formulated a number of policies, such as the *Three-year Action Plan for Rural Living Environment Improvement Guiding Suggestions* related to promoting the special action of the "Toilet Revolution" in rural areas, aiming to improve the prevalence of sanitary toilets and the utilization rate of toilet excreta as a resource. Chinese statistics have shown that as of 2020, the usage rate of rural sanitary toilets in China has greatly improved, from 7.5% (1993) to 68% (2020), with an increase of about 5% per year, and more than 40 million rural household toilets have been renovated in total. China has a long history of using human excreta in agriculture, with farmers generally viewing latrine waste as a "valuable fertilizer" (Ferguson, 2014). Solid feces' composition encompasses a large amount of organic matter, which makes it possible to turn it into biofuel (Abomohra et al., 2020). However, feces that are not effectively treated can cause the spread of diseases through fecal–oral routes, especially in children and immunocompromised pregnant women (Majorin et al., 2017). Therefore, the focus has generally shifted toward increasing people's access to toilets and ensuring that the handling of human excreta complies with public health standards.

China lacks a comprehensive means of evaluation of the effectiveness of toilet retrofitting in rural areas, and the environmental and social benefits of toilet retrofitting remain ill-defined (Ma et al., 2021). Most studies have focused on social surveys, including those on the penetration rate of sanitary toilets and the perceptions of rural households (Angelakis et al., 2015). For example, a recent survey of 980 rural households from 22 provinces across China reported on farmer households' satisfaction with toilet retrofitting (Zhou et al., 2022). In addition, based on interviews with 414 residents from 13 villages across three provinces in the west of China, a study analyzed the current situation and attitudes related to possible changes in the rural sanitation service chain (Guo et al., 2021). Recently, sporadic studies evaluating the effects of toilet retrofitting have gradually emerged, but most of these are limited to small areas or evaluation methodology. Li et al. (2021) used system dynamics to assess the effect of toilet improvements in Jiaozhou, China. Zhu et al. (2021) assessed indicators and ranked their weights in relation to the innovation of toilet technologies *via* the analytic hierarchy process and life cycle assessment methods. These studies do not reflect the overall effectiveness of rural toilet retrofitting in China. The pollution load of feces after toilet retrofitting, whether the feces can be harmless, whether the sanitary environment meets the requirements of national standards, whether toilet operation, and maintenance can be long-lasting, etc., remain unknown (Zhang et al., 2020).

According to the China Health and Family Planning Statistical Yearbook, the number of three-compartment septic tanks exceeded 80 million by the end of 2017, accounting for 37.6% of the total of number of rural sanitary household toilets in China. In water-scarce and cold areas, composting toilets were regarded as the most popular toilet model. Therefore, here, we evaluated the effects of retrofitting three-compartment septic tanks and composting toilets in rural China from the two aspects of the environment and society, to improve the effects of the current rural toilet retrofitting approach. These results provide basic data and references for establishing a scientific and appropriate evaluation index system for rural toilet retrofitting and provide a scientific basis as well as policy advice related to optimizing rural toilets and improving the quality of rural toilet retrofitting.

2 METHODS AND MATERIALS

2.1 Sample Collection

In this study, composting toilet samples were collected from Heilongjiang Province (HLJ), Jilin Province (JL), Gansu Province (GS), and Inner Mongolia Autonomous Region (Inner Mongolia: NM), which belong to the northwest region, 5 in each province, with a total of 20 samples. A total of 30 samples of three-compartment septic tank effluent in the southeastern region were collected from Shandong Province (SD), Ningxia Hui Autonomous Region (Ningxia: NX), Jiangsu Province (JS), Shaanxi Province (SX), Hunan Province (HN), and Hubei Province (HB) were collected, which also corresponded to five samples per province (**Figure 1**).

2.2 Questionnaire

To ensure that the questionnaire was scientific, authentic, and representative, this survey adopted a random survey. For some rural residents who were unable to accurately express the contents of the questionnaire, we invited people with higher education (high school degree or above) to retell it with their consent. In addition, we assured the participants that their answers were private, anonymous, and confidential to encourage them to express their opinions freely. The surveyed households in each province had the same toilet mode and had similar usage time. Fifty questionnaires were valid. The contents of the questionnaire included the total population, population structure, existing toilet patterns, toilet sewage treatment methods, septic tank cleaning frequency, toilet use time, etc.

2.3 Sample Monitoring

Measurements of total nitrogen (TN), total phosphorus (TP), organic matter (OM), and pH for composting toilet samples were obtained using organic fertilizers (NY/T 525-2021) (Wei et al., 2021). After the septic tank water sample was filtered through a 0.45 μm membrane, the total nitrogen (TN), total phosphorus (TP), ammonium nitrogen (NH_4^+-N), and nitrous nitrogen (NO_3^--N) in the water sample were detected using a continuous flow analyzer (Skalar SAN+, the Netherlands) according to the method described (Martínez Salgado et al., 2019). The number of fecal coliforms and the mortality rate of aphid eggs and *Salmonella* were measured in accordance with the standard hygienic requirements for harmless disposal of night soil (GB7959-2012) (Pathma and Sakthivel, 2012).

2.4 Data Analysis

SPSS 20.0 was used to analyze the intra-group samples by one-way variance (ANOVA), and the least significant difference (LSD) test was used for statistical comparison. In addition, the reliability of the recovered questionnaire was tested using SPSS 20.0 software. The

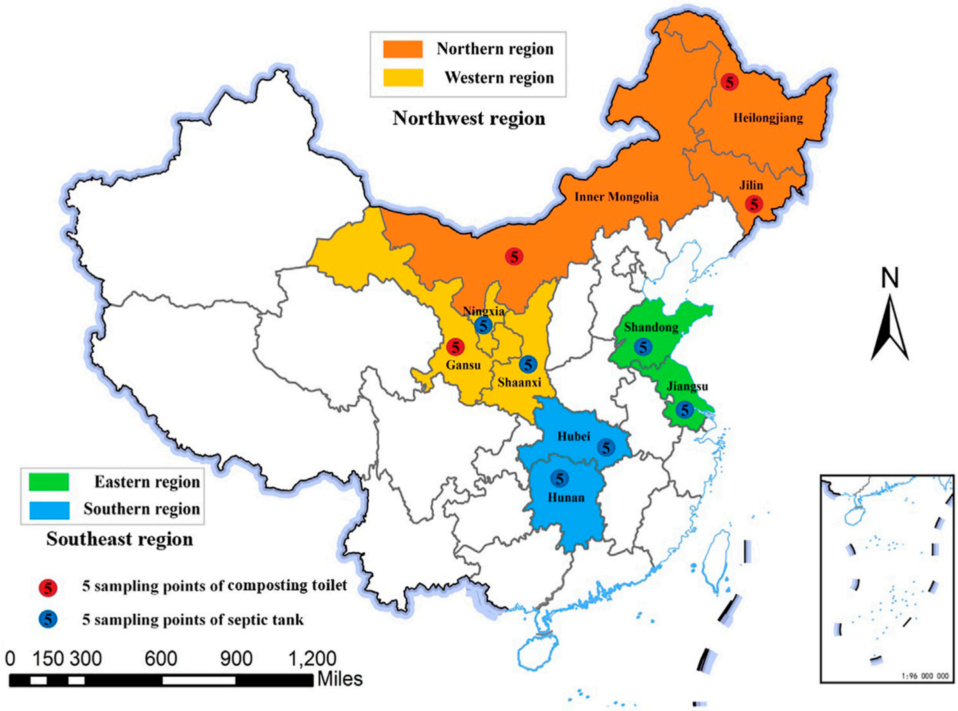

FIGURE 1 | Map of the samples of excrement from 50 rural household toilets.

physical and chemical indicators of the samples were plotted using ggbetweenstats in ggstatsplot (R 4.0.3).

2.5 Fuzzy Evaluation Method

Here, we chose the fuzzy synthetic evaluation method, which mainly converts qualitative evaluation into quantitative according to the membership theory of fuzzy mathematics; that is, we used fuzzy mathematics to make an overall evaluation of objects or objects restricted by multiple factors, and it can better solve vague and difficult to quantify problems, which is suitable for evaluation involving subjective indicators in this study. The basic processes of fuzzy synthetic evaluation were shown as follows:

1) determine a set of evaluation objects;
2) structural evaluation grade;
3) fuzzy synthetic evaluation is used to determine the subordination degree of a single factor;
4) building a fuzzy evaluation matrix; and
5) the overall evaluation results were calculated.

3 RESULTS AND DISCUSSION

3.1 Environmental Effect of Feces After Toilet Retrofitting

3.1.1 Physiochemical Characteristics

Figure 2 shows the contents of physical and chemical indicators in all samples. It was observed that the TN and TP contents in composting toilet samples ranged from 259.21 to 330.46 mg/kg and 2.71 to 3.71 mg/kg, respectively, and the samples in Jilin Province were found to have the highest TN content, while Inner Mongolian samples had the lowest TN content. Gansu Province's composting toilet samples had the highest TP content at 3.71 mg/kg, whereas the lowest level was detected at 2.71 mg/kg in Jilin Province. In addition, the contents of NH_4^+-N and NO_3^--N in composting toilet samples in four provinces ranged from 15.6 to 50.16 mg/kg and 8.51–24.45 mg/kg, respectively. The organic content (OM) of feces was 110.78–274.10 g/kg (Gansu > Heilongjiang > Jilin > Inner Mongolia). The nutritional levels of the treatment products of composting toilets (259.21–330.46 mg/kg) in this study were lower than in previous studies (720–950 mg/kg), probably due to the use of different bulking materials (Kelova et al., 2021). However, it should not be overlooked that this concentration can still fulfill the nutrient needs of crops and can thus replace the use of chemical fertilizers and help close the nutrient cycle loop. Anand and Apul (2014) estimated that 4.9–6.4% of annual commercial fertilizers used in Australia could be replaced with human feces. Mature compost can also be used as an amendment, substituting other materials used for soil remediation (Vinnerås et al., 2003). Therefore, as a type of toilet with no flush, composting toilets can offer a sustainable solution to the problem of water and resource reuse.

In septic tank effluent, the concentrations of TN, TP, and organic carbon were observed at 381.31–2040.84 mg/L, 10.41–80.46 mg/L, and 66.32–1,003.01 mg/L, respectively, and showed no significant differences between provinces ($p > 0.05$)

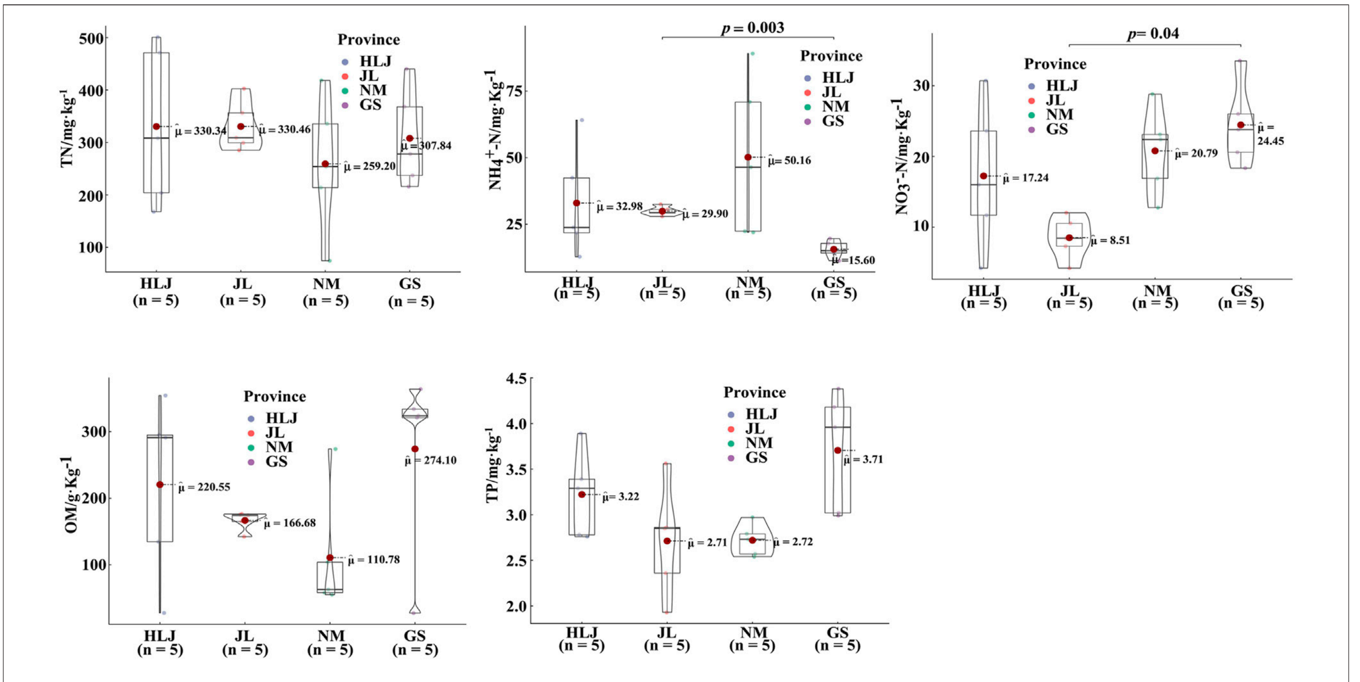

FIGURE 2 | The physiochemical indicators of composting toilet samples. The figure shows box plots, dot plots and violin plots of TN, TP, NH_4^+-N, NO_3-N and OM in different provinces, in which û represents the mean of 5 samples and n represents the number of samples. HLJ, JL, NM and GS represent Heilongjiang Province, Jilin province, Inner Mongolia Autonomous Region (Inner Mongolia) and Gansu province; annotate the pairwise comparisons using p-values.

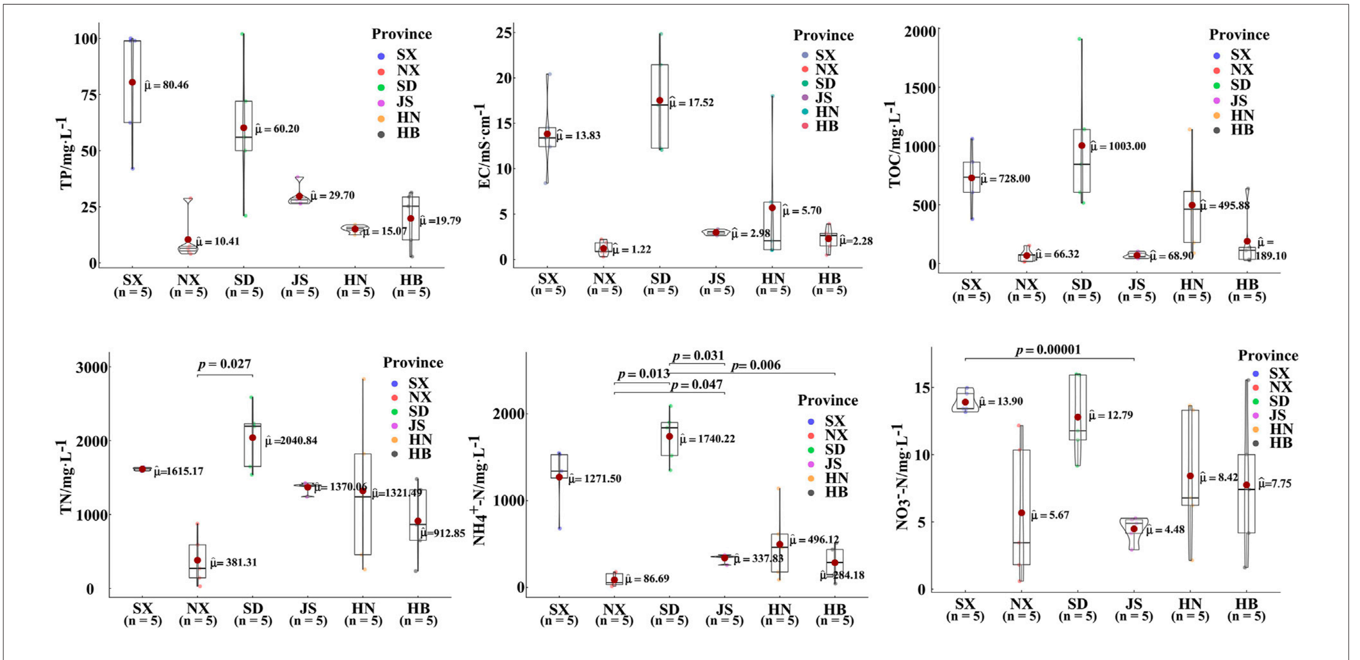

FIGURE 3 | The physiochemical indicators of three-compartment septic tank effluent. The figure shows box plots, dot plots and violin plots of TN, TP, NH_4^+-N, NO_3-N, TOC and EC in different provinces, in which û represents the mean of 5 samples and n represents the number of samples. SX, NX, SD, JS, HN and HB represent Shaanxi province, Ningxia Hui Autonomous Region (Ningxia), Shandong province, Jiangsu province, Hunan province and Hubei province.

(**Figure 3**). The results were higher than those in previous studies, which showed TN and NH_4^+-N concentrations at 194.8–411.16 mg/L and 160.4–322.76 mg/L, respectively, based on 57 septic tanks in six provinces of China (Wang et al., 2021). Combined with on-site sampling, it was found that the collected effluent was relatively turbid, especially in Shaanxi, Shandong, and Hunan provinces. According to the feedback of the surveyed rural residents, since these were newly rebuilt septic tanks, the use time was between 2 and 3 months, thus the feces remained for a relatively short period in the septic tank to ferment, compared with the findings of the study of Wang et al. This explains why the physiochemical indicators of the effluent in this study were higher than those in other studies (Tan et al., 2021; Cui et al., 2006). In addition, our investigation found that the rural residents in Ningxia, Jiangsu, and Hunan provinces have the habit of discharging domestic water into septic tanks. The dilution effect of the domestic water may cause the chemical indicators of the septic tank effluent in this area to be lower than those in the province. In particular, due to the shortage of local water resources in the Ningxia region, domestic water was temporarily stored to flush the toilets; however, the mixing of domestic wastewater into septic tanks meant that the residence time of the manure failed to meet the standard requirements. The direct use of agriculture not only pollutes the soil environment but also increases the risk to human health. When feces is left in the open, there is a higher risk that humans, especially children, may come into direct contact with fecal pathogens (Majorin et al., 2017). The children are at a higher risk of exposure to fecal–oral pathogens because they play on the ground, and place their hands near their faces and in their mouths (Bawankule et al., 2017; Islam et al., 2018). Fecal–oral pathogens can cause diarrheal illnesses, which can lead to stunting, a condition that affects 162 million children worldwide (Beardsley et al., 2021).

In addition, the results show that the electrical conductivity of the septic tank effluent in Shaanxi and Shandong provinces was relatively high, far exceeding the total salt control limitation given by the Standard for Irrigation Water Quality (GB 5084-2021). Salinity is abiotic stress that harms agriculture by decreasing productivity. High electrical conductivity has a negative impact on the morphological and biochemical functions of plants, which can inhibit seed germination, plant growth, development, and yield (Arif et al., 2020). Moreover, high electrical conductivity hampers photosynthetic machinery, transpiration, and gaseous exchange by decreasing the content of chlorophyll and carotenoids and distorting the chloroplast ultrastructure and PSII system (Pan et al., 2021). High electrical conductivity lowers the soil water potential and leaf water potential, thus disturbing plant–water relations and reducing the turgor of the plant, which ultimately leads to osmotic stress (Navada et al., 2020). Plants take up salt from the soil *via* transporters that create ion toxicity and disturb mineral uptake and ion homeostasis. Salinity leads to the extensive accumulation of ions (Na^+ and $Cl^−$) and inhibits K^+ and Ca^{2+} uptake, thus resulting in ionic imbalance (Isayenkov and Maathuis, 2019). Therefore, septic tank effluent resources in this area should be diluted first and then returned to the field. This could prevent the soil salinization caused by high salt accumulation. In the future, more long-term positioning studies should focus on the effects of manure return on crop absorption and soil salt accumulation.

The pH values of composting toilet samples and septic tank effluent were found to be alkaline, with an average value between 7.32 and 8.37 (**Figure 4**), suggesting that some of the effluents from the septic tank cannot be used directly for the irrigation of

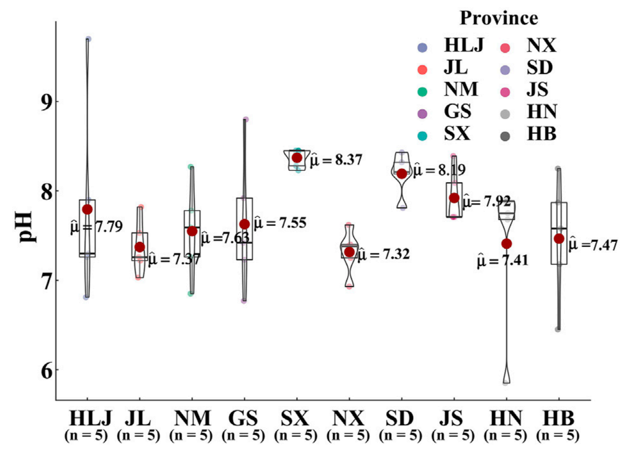

FIGURE 4 | The pH of toilet feces surveyed in 10 provinces (regions). The figure shows box plots, dot plots and violin plots of fecal distribution in different provinces, in which û represents the mean of 5 samples and n represents the number of samples.

farmlands as high pH conditions could cause the exchangeable moiety to combine with other anions and increase the heavy metal content in the soil (Ouyang et al., 2020). Furthermore, high pH levels lead to low soil organic matter content; strong acid leaching; poor texture; poor structure; soil consolidation; poor ventilation; water permeability; the incoordination of soil water, air, and heat; easy erosion; soil erosion; and soil fertility, which are all disadvantageous for tillage and plant growth (Köninger et al., 2021).

3.1.2 Harmlessness of Toilet Excreta

Fecal coliform, *Salmonella*, and Ascaris eggs are regarded as important indices of harmlessness. With reference to the Hygienic Standard for the Harmlessness of Feces (GB 7959-2012), we have here defined qualified samples as those with a mean level of fecal coliforms between $10^{−1}$ and $10^{−2}$, a mortality rate of Ascaris eggs >95%, and no *Salmonella* was detected. Among the 50 toilet fecal samples, the total rate of qualified fecal coliform bacteria was 84%, the total mortality of Ascaris eggs reached 90%, and *Salmonella* was not detected in any samples (**Table 1**). Specifically, the average qualified rates of fecal coliform bacteria and Ascaris eggs in the compost toilet samples were 70 and 80%, respectively, while the two qualified rates of septic tank effluent were 93.3 and 96.7%, respectively, indicating that the harmlessness of the feces treated in the three-compartment septic tank was significantly higher than that in composting toilets ($p < 0.01$). Among them, the composting toilets adopted in the northwest were generally unable to achieve harmlessness, especially in the Inner Mongolia region, as the conditions affecting the process of composting were not sufficient. As previously stated, the key to composting treatment is fermentation, and many external factors including water content and temperature restrict the degradation effect, and it is thus here proposed to optimize composting toilet technology and thus improve the level of harmlessness (Hill and Baldwin, 2012). As for three-compartment septic tanks, although the effect

TABLE 1 | The qualified rate of harmless treatment of feces after toilet modification.

Provinces (autonomous regions)	Sample types	Qualified rate of fecal coliform group value	Qualified rate of mortality of Ascaris lumbricoides eggs	Qualified rate of salmonella value
Heilongjiang	Composting toilets	80%	80%	100%
Jilin		80%	100%	100%
Gansu		60%	80%	100%
Inner Mongolia		60%	60%	100%
Shaanxi	The effluent of three compartment septic tank	80%	100%	100%
Ningxia		80%	80%	100%
Shandong		100%	100%	100%
Jiangsu		100%	100%	100%
Hunan		100%	100%	100%
Hubei		100%	100%	100%

of treatment on pathogenic factors was better than that in the composting toilet, it was still lower than that required by the public health body, which is in line with the findings of the study by Lusk et al. (2017). The report of Tollestrup et al. (2014) also raised the fact that the dispersal of septic tank effluents can contribute to increasing the incidence of infectious diseases.

Fortunately, compared with previously used rural toilets, the degree of harmlessness of feces after toilet retrofitting increases to a certain extent (Gao et al., 2017). This can act as a reference for promoting new sanitation practices that enhance the availability and sustainability of water and sanitation services in other low- to middle-income countries worldwide, which will ultimately contribute to achieving Sustainable Development Goal 6: ensure availability and sustainable management of water and sanitation for all.

3.2 Social Effect of Toilet Retrofitting

The indicators of the effects of toilet retrofitting were determined with reference to the standards and policy documents regarding rural areas in China, and the quantitative values of the influencing factors were provided by means of expert consultation and scoring. The 24 participants in the consultation and scoring process included government officials and scientific researchers in related academic fields. Additionally, it was determined that the manure utilization index had the highest weight among the other first-level indicators, in terms of the national demand orientation, the focus of grassroots work, and public feedback. The weight of each indicator was obtained based on the opinions of experts, as shown in **Table 2**.

3.2.1 Determine the Index Weight

1) Determine a set of evaluation objects

Total object set: A (effect of rural toilet retrofitting) = {E1,E2,E3,E4} = {Toilet construction, Mass satisfaction, Manure utilization, Later management, and maintenance}; various levels of index set: B1 (toilet construction) = {C1 (toilet house construction), C2 (underground construction), C3 (toilet product quality)}; B2 (mass satisfaction) = {C4 (easy operation), C5 (cost expenditure), C6 (toilet environment)}; B3 (manure utilization) =

TABLE 2 | Evaluation index system of toilet improvement in rural areas.

First-level index	Index weight	Secondary index	Index weight	Assessment factors
Toilet construction	0.25	Toilet house construction	0.1/0.4	Whether the construction of toilet houses meets the requirements of national standards, and whether the location of toilets is reasonable,
		Underground part construction	0.1/0.4	Whether the construction, construction and use of water and aqua privies meet the requirements of national standards
		Toilet product quality	0.05/0.2	The appearance and structural proportion of toilet products meet the national design requirements.
Mass satisfaction	0.2	Easy to use	0.05/0.25	Whether the old toilet will be demolished after the new toilet is built, and whether the new toilet will be abandoned.
		Cost expenditure	0.05/0.25	Toilet reconstruction expenses, daily use expenses and later operation and maintenance expenses
		Toilet environment	0.1/0.5	The toilet house is odorless, free of mosquitoes and flies, and ventilated.
Fecal utilization	0.3	Harmless treatment	0.1/ (1/3)	Whether the type of toilet is harmless sanitary toilet
		Resource utilization	0.1/ (1/3)	Whether to carry out unified treatment after returning to the field, composting or clearing
		Environmental risk of faeces	0.1/ (1/3)	There is no leakage in the septic storage tank, and the feces are not dumped at random.
Later stage management and protection	0.25	Regular maintenance of toilet products	0.1/0.4	Professional operation and maintenance team
		Establish a management and protection mechanism	0.1/0.4	Whether the local government has established the dung removal and transfer mechanism and whether the mechanism is normal.
		Incorporate into the village rules and regulations	0.05/0.2	Raise villagers' awareness of hygiene

{C7 (harmless treatment), C8 (utilization of resources), C9 (environmental risk of feces)}; B4 (later management and maintenance) = {C10 (regular maintenance of toilet products), C11 (establishment of management and maintenance mechanism), C12 (incorporated into village regulations)}.

2) Structural evaluation grade

We constructed an evaluation level set to score each indicator and thus obtain relative scores. This study established five relatively fair evaluation level matrices. The percentile system is easy to operate and widely used. In order to avoid the problems of the percentile system being dominated by subjectivity and poor objectivity, here, we have used "very satisfied, relatively satisfied, general, dissatisfied, and extremely dissatisfied" grades, which help to effectively overcome the differences in the professional knowledge of the evaluators. Hence, S = {very satisfied, relatively satisfied, general, dissatisfied, extremely dissatisfied} = {100, 80, 60, 40, 20} (Lu and Xu, 2011).

3) The fuzzy evaluation method was used to determine the subordination degree of a single factor in the effective evaluation of rural toilet retrofitting.

Taking the Inner Mongolia region as an example, the single-factor membership degree of the rural toilet renovation effect is presented in **Table 3**.

4) Building a fuzzy evaluation matrix

Based on the statistics related to the obtained data and combined with the use of the fuzzy comprehensive evaluation method, the first-level fuzzy evaluation matrix of the rural toilet retrofitting effect was determined to be E1, E2, E3, and E4, respectively.

$$E_1 = \begin{bmatrix} \frac{1}{5} & \frac{2}{5} & \frac{1}{5} & \frac{1}{5} & \frac{0}{5} \\ \frac{2}{5} & \frac{2}{5} & \frac{1}{5} & \frac{0}{5} & \frac{0}{5} \\ \frac{1}{5} & \frac{1}{5} & \frac{2}{5} & \frac{1}{5} & \frac{0}{5} \end{bmatrix} E_2 = \begin{bmatrix} \frac{4}{5} & \frac{1}{5} & \frac{0}{5} & \frac{0}{5} & \frac{0}{5} \\ \frac{1}{5} & \frac{1}{5} & \frac{2}{5} & \frac{0}{5} & \frac{1}{5} \\ \frac{0}{5} & \frac{1}{5} & \frac{3}{5} & \frac{1}{5} & \frac{0}{5} \end{bmatrix}$$

$$E_3 = \begin{bmatrix} \frac{1}{5} & \frac{2}{5} & \frac{2}{5} & \frac{0}{5} & \frac{0}{5} \\ \frac{3}{5} & \frac{1}{5} & \frac{1}{5} & \frac{0}{5} & \frac{0}{5} \\ \frac{0}{5} & \frac{1}{5} & \frac{2}{5} & \frac{2}{5} & \frac{0}{5} \end{bmatrix} E_4 = \begin{bmatrix} \frac{0}{5} & \frac{1}{5} & \frac{1}{5} & \frac{2}{5} & \frac{1}{5} \\ \frac{0}{5} & \frac{1}{5} & \frac{1}{5} & \frac{2}{5} & \frac{1}{5} \\ \frac{5}{5} & \frac{0}{5} & \frac{0}{5} & \frac{0}{5} & \frac{0}{5} \end{bmatrix}.$$

3.2.2 Effect Evaluation

According to formula F=Wi*E, where Wi represents a collection of indicator weights for individual layers, a fuzzy evaluation calculation is performed on indicators B1, B2, B3, and B4. E1 is the first level of the toilet construction indicator fuzzy comprehensive evaluation:

$$F_1 = w_1 * E_1 = (0.4, 0.4, 0.2) * \begin{bmatrix} \frac{1}{5} & \frac{2}{5} & \frac{1}{5} & \frac{1}{5} & \frac{0}{5} \\ \frac{2}{5} & \frac{2}{5} & \frac{1}{5} & \frac{0}{5} & \frac{0}{5} \\ \frac{1}{5} & \frac{1}{5} & \frac{2}{5} & \frac{1}{5} & \frac{0}{5} \end{bmatrix} = (0.28, 0.36, 0.24, 0.12, 0). \quad (1)$$

Similarly, the fuzzy ratings for E2, E3, and E4 are F2 = W2*E2= (0.25, 0.2, 0.4, 0.1, 0.05), F3 = W3*E3= (0.27,0.27,0.33,0.13,0), and F4 = W4*E4= (0.2,0.16,0.16,0.32,0.16).

According to the second-level evaluation formula,

$$F = W * E = (0.25, 0.2, 0.3, 0.25) * \begin{bmatrix} 0.28 & 0.36 & 0.24 & 0.12 & 0 \\ 0.25 & 0.2 & 0.4 & 0.1 & 0.05 \\ 0.27 & 0.27 & 0.33 & 0.13 & 0 \\ 0.2 & 0.16 & 0.16 & 0.32 & 0.16 \end{bmatrix} = (0.251, 0.251, 0.279, 0.169, 0.05).$$

The weighted average method was used to calculate the comprehensive evaluation score of the rural toilet retrofitting effect in Inner Mongolia (Y = 70.67). Similarly, the comprehensive evaluation scores of the secondary indices were as follows: Y1 = 76, Y2 = 70, Y3 = 73.6, and Y4 = 58.4.

TABLE 3 | Single factor membership degree of toilet improvement effect in rural areas of Inner Mongolia.

Evaluation index	Very satisfied	More satisfied	General	Not satisfied	Extremely unsatisfied
Toilet house construction C1	1	2	1	1	0
Underground part construction C2	2	2	1	0	0
Toilet product quality	1	1	2	1	0
Easy to use C3	4	1	0	0	0
Cost expenditure C4	1	1	2	0	1
Toilet environment C5	0	1	3	1	0
Harmless treatment C6	1	2	2	0	0
Resource utilization C7	3	1	1	0	0
Environmental risk of faeces C8	0	1	2	2	0
Regular maintenance of toilet products C9	0	1	1	2	1
Establish a management and protection mechanism C10	0	1	1	2	1
Incorporate into the village rules and regulations C11	5	0	0	0	0

TABLE 4 | Comprehensive score and second-level index score of changing rural toilets into toilets in 10 provinces (autonomous regions).

Provinces (autonomous regions)	Comprehensive evaluation score (Y)	Toilet construction (Y1)	Mass satisfaction (Y2)	Fecal utilization (Y3)	Later stage management and protection (Y4)
Heilongjiang	64.2	66.4	67	65.3	58.4
Jilin	72.6	85.6	79	62.7	66.4
Gansu	64.6	71.2	63	62.7	61.6
Heilongjiang	63.6	70.4	61	62.7	60
Shaanxi	72.6	83.2	80	64	66.4
Ningxia	82	81.6	93	77.3	79.2
Shandong	92.4	95.5	98	82.7	96.8
Jiangsu	91.8	94.4	95	88	91.2
Hunan	91.8	95.2	91	86.7	95.2
Inner Mongolia	70.67	76	70	73.6	58.4

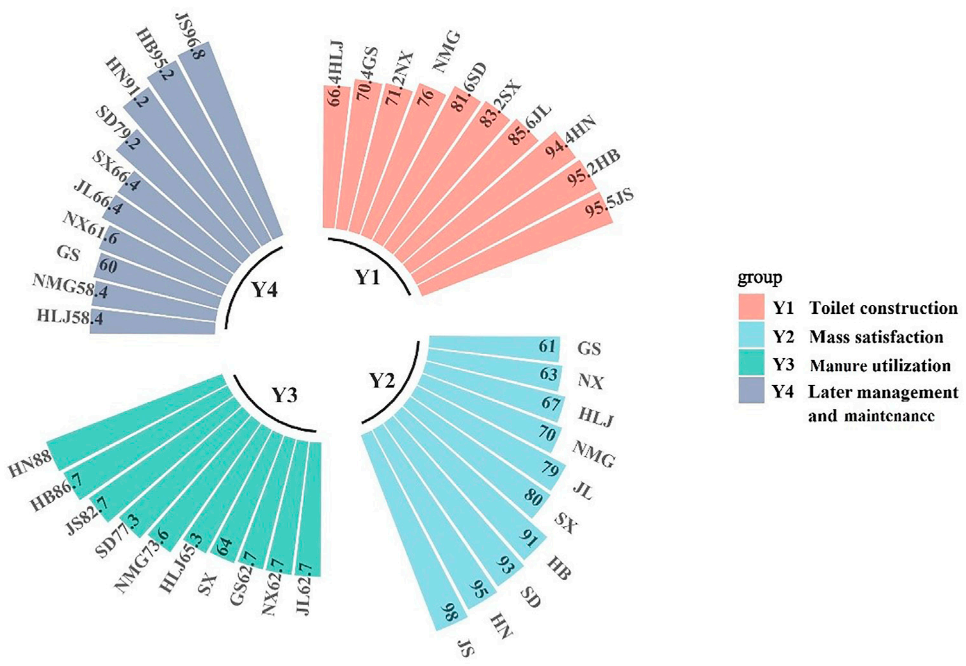

FIGURE 5 | Comprehensive scores of fuzzy evaluations of the second-level indicators of 10 provinces (regions).

The comprehensive evaluation scores of rural toilet retrofitting in other provinces were in line with those of Inner Mongolia. The comprehensive and secondary index scores of the ten provinces are shown in **Table 4**. The results show that Jiangsu Province had the highest comprehensive evaluation score of 92.4 followed by Hunan and Hubei provinces, both with 91.8, whereas Gansu Province had the lowest score of 63.6. Overall, the scores showed a "high southeast, low northwest" trend. In the toilet construction indicator layer, Hunan, Hubei, and Jilin provinces had scores higher than 85, whereas the northwest region's scores were generally low, with Heilongjiang Province achieving the lowest score of 66.4 (**Figure 5**). In the mass satisfaction indicator layer, the scores of the four provinces in the southeastern region were all above 90. The scores of the six provinces in the northwest region ranged from 60 to 80, showing a polarization trend and the scores of the manure utilization index layer generally exhibited a trend of southern > eastern > northwestern. In the later management and maintenance index layer, the scores of Jiangsu, Hunan, and Hubei provinces were much higher than those of other provinces; Jiangsu Province had the highest score of 96.8, whereas Ningxia and Jilin provinces had the lowest scores of only 62.7. Overall, composting toilets are less acceptable in the rural areas than three-compartment septic tank toilets. Rural residents are reluctant to accept the technology because of perceived odor and maintenance issues. Composting toilets require the user to be more active in managing their waste compared to the flush model used in the developed areas. Maintenance requirements such as the turning of the compost, the addition of bulking agents, emptying the chamber, and cleaning the toilet without using much water are unacceptable to the rural residents. In addition, the composting toilets may be perceived as second-class, inconvenient, and burdensome, all of which perceptions would limit the adoption of the technology (Anand and Apul, 2014). However, our results differ from those of Gao et al. (2017), who believed that the composting toilets should be given more attention due to their suitability, as they can be used in water shortage and cold conditions.

Consequently, the comprehensive evaluation scores of toilets retrofitting in Shandong, Jiangsu, Hunan, and Hubei provinces were found to be "relatively satisfied" and "very satisfied." The scores in Heilongjiang, Jilin, Ningxia Hui, Gansu, Shaanxi, and Inner Mongolia were between average and relatively satisfactory. These results indicate that the rural residents were satisfied with the improvements to rural toilets, but the evaluation *via* secondary indicators shows that some problems remain. Heilongjiang Province achieved the lowest score for toilet construction mainly because the five households surveyed stated low satisfaction with the construction of toilet houses, most of which have leakage problems. The satisfaction levels of the surveyed rural residents in Ningxia and Gansu provinces were relatively low mainly because they were dissatisfied with the convenience of using composting toilets. According to rural residents' feedback, compost toilets are only suitable for two to three people. When there are a large number of users, the efficiency of the toilet is greatly reduced, and it may even stop functioning. With regard to manure utilization, the scores in the provinces (regions) were higher, reflecting the significant development trend in the utilization of manure resources in China's rural environment. However, the low scores pertaining to the harmlessness treatment and environmental risk indicators of fecal contamination indicate that the provinces (regions) were not yet fully equipped with technologies and facilities for fecal treatment and recycling, and they need to be further strengthened. It is worth noting that the scores may not reflect the actual situation, due to the small number of samples, and certain errors may arise during the sampling and investigation that mean our results cannot be used as a guiding document.

4 CONCLUSION AND OUTLOOK

Based on the monitoring of the physiochemical properties and degree of harmlessness of toilet sewage, as well as the comprehensive evaluation of the mass satisfaction, manure utilization, and consequential management and maintenance following toilet retrofitting, in relation to 50 rural residents in 10 provinces (regions) of China, it can be concluded that the effectiveness of rural toilets after retrofitting was remarkable. The comprehensive evaluations of the ten provinces (regions) gave results that were between average and very satisfied, but the construction of toilet houses, the utilization of manure resources, and the consequential management and maintenance still need to be strengthened by government investment and technical guidance. In accordance with our evaluation results, we make the following four suggestions for the improvement of toilets in rural areas in the future:

1) The development of suitable technical models for toilet retrofitting in Northwest China. The existing composting toilets are generally unable to make feces harmless, and the satisfaction of the masses is low due to disadvantages such as strong odors and low fermentation efficiency. We should thus aim to make developments in technologies such as antifreeze, water preservation, and efficient fermentation in the future.
2) In areas with abundant water resources and strong economic conditions, it is recommended to popularize flushing toilets, which allow for better fecal treatment, but we need to be on guard against the potential risk of diseases related to the flushing treatment.
3) A standard system of toilet retrofitting in rural areas should be established and perfected, and the quality, construction, and acceptance level of toilets should be strictly controlled to avoid the environmental pollution and irregular operation caused by poor toilet quality.
4) Improving the utilization rate of manure resources and strengthening the research on subsequent manure utilization technology will be the next priority to limit the environmental health risks caused by manure applications.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

YG and LT designed and conducted the experiments, collected samples, and analyzed data. XZ and YX directed the experimental design and overall concept and provided guidance to YG. CZ, QL, and XW: investigation. BY and PC: methodology.

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