Ecological-economic assessment of ecological sanitation development in the cities of Chinese Loess Plateau

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ABSTRACT

Many cities in Chinese Loess Plateau have inadequate sanitation. Ecological sanitation (ecosan) is a systemic approach to solve environmental and sanitary problems. Thus, suitable ecosan technologies and systems were analyzed, and three alternative developing models of sanitation were compared, namely, centralized traditional (CT) model, centralized ecosan (CE) model, and centralized and decentralized mixed ecosan (ME) model. Their ecological-economic assessment was made in the theoretical framework of social-economic-natural complex ecological system. Main results were (1) CE and ME reduced the emission of greenhouse gases, and the maximum reduction was 96.8% of CT. (2) ME reduced the water pollutants at a comparatively lower capital and running cost, and BOD₅ emission could be reduced to 85–88% of CT. (3) CE and ME reclaimed more nutrients than CT. Attributing to reclaiming nutrients, CE and ME could produce 461.4 and 809.9 Gg foods, respectively, and CT was 32.1 Gg. (4) The sequence of health risk caused by sanitation was CT > CE > ME. (5) Urban ecosan system could bring forward a maximum net benefit of 0.267 billion RMB. In addition, the bottlenecks of developing ecosan in China were also discussed in this paper.

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1. Introduction

Organic wastes discharged from urban communities (including food waste, faeces, urine, and grey water) have been given more attention due to their global and regional ecological impacts. For example, uncontrolled waste landfill disposal sites, sewage ponds, and sludge digest facilities account for 10% of the greenhouse gases (GHGs) emission in China (Office of National Coordination Committee on Climate Change, 2001). Organic wastes result in health problems, such as diarrhea, hepatitis, and cancer, by means of contaminating water and food (Xu et al., 2003; Winblad and Hebert, 2006). Urbanization in China is occurring rapidly and many newly built urban areas are facing problems of inadequate sanitation services. Only 72% Chinese cities could access to freshwater that reached the national standard (year 2006).

Ecological sanitation (ecosan) is a systemic approach to solve environmental and sanitary problems. The basic principle of ecosan is “respect the ecological integrity in the sanitary systems” (Black, 2001; Langergraber and Muellegger, 2005). Ecosan focuses on the harmless treatment of the waste and security of fresh water. Water, nutrient, and biogas are recycled and the ecological loop of materials and energy is closed (Black, 2001; Winblad and Hebert,

2006). But some disadvantages of urban ecosan systems, such as psychosocial acceptance and public management difficulties, also have been found (Dellstrom Rosenquist, 2005).

Urban ecosan systems are varied in the different regions of China, which may be attributed to the geographic, economic, and cultural differences. In China, the northwest has lower temperatures and is semiarid; the southwest is temperate and moist; the northeast has very low temperatures in winter and remains frozen; the middle and the coastal areas are temperate and rainy. At the same time, the social and economic differences are evident. The West is less developed than the East and the coastal areas. Therefore, the regional differences should be respected when developing ecosan systems in China (Wang and Zhou, 2007).

Objective and comprehensive ecological-economic assessment was needed to develop urban ecosan systems in China since it is useful in the promotion of support for finances, policies, and legislations (Wang and Zhou, 2007). There are several methods for assessing solid waste and wastewater management systems. Life cycle analysis (LCA) was a useful method to identify and calculate the systemic material flow of pollutants and nutrients (Lundie and Peters, 2005; Shmelev and Powell, 2006), while the organic waste research (ORWARE) model could precisely perform a substance-flow simulation and find a relationship between substance-flow and economic benefits (Sonesson et al., 2000). There were two studies that integrated solid waste and wastewater system in the city level, and the factors of pollutions, recyclable nutrients,

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consumption of energy, cost, and benefits were assessed (Sonesson et al., 2000; Magid et al., 2006). However, the ecosan system is a complex eco-system that integrated social, economic, and natural factors (Wang, 2001; Dellstrom Rosenquist, 2005; Magid et al., 2006; Nawab et al., 2006), wherein a comprehensive framework of different subsystems should be established for understanding and unravelling complexity (Tainter, 2006; Saravanan, 2008).

The Loess Plateau is a typical semiarid region on the upper reaches of the Yellow River in the west of China (see Fig. 1). Fifty-one cities of eighteen million people in this region (belonging to Ningxia, Shaanxi, Gansu, Shanxi, and Inner Mongolia Province) are facing problems of inadequate sanitation and lack fresh water. With the consideration of regional differences in sanitation, we analyzed suitable ecosan technologies and integrated eight ecosan systems, and then established three ecosan developing models for the study area. In addition, the developing models of ecosan were assessed based on the theoretical framework of social–economic–natural complex ecological system (Ma and Wang, 1984).

2. Methods

2.1. Matrix of unit technologies

Ecosan is a system that integrated different unit technologies aiming for sustainable use of organic solid waste, faeces, urine, and grey water. Furthermore, there are two organization ways of technologies, namely, centralized and decentralized technologies (Magid et al., 2006). Thus, matrix of sanitary technologies is as follows:

$$\begin{bmatrix} \text{Organic solid waste} \\ \text{M1 Centralized landfill} \\ \text{M2 Centralized compost} \\ \text{M3 Centralized digest} \\ \text{M4 Decentralized compost} \\ \text{M5 Decentralized digest} \end{bmatrix} \times \begin{bmatrix} \text{Faeces} \\ \text{F1 Centralized sewage plant} \\ \text{F2 Centralized faeces plant} \\ \text{F3 Decentralized compost} \\ \text{F4 Decentralized digest} \end{bmatrix} \times \begin{bmatrix} \text{Urine} \\ \text{U1 Centralized sewage plant} \\ \text{U2 Centralized faeces plant} \\ \text{U3 Decentralized digest} \\ \text{U4 Storage} \end{bmatrix} \times \begin{bmatrix} \text{Grey water} \\ \text{S1 Centralized sewage plant} \\ \text{S2 Decentralized sewage facility} \end{bmatrix} \quad (1)$$

Feasibility and applicability of unit technologies should be analyzed before integrating ecosan systems. First, both centralized and decentralized systems are available for urban sanitation. Centralized technologies were generally applied in urban areas, such as landfills, digesting sites, and sewage plants, especially in the already built urban areas. The decentralized technologies were also important for sustainable sanitation (Otterpohl et al., 1997; Wilderer and Schreffl, 2000). Many newly built urban communities of Beijing, Shanghai, Ningbo, Jinhua, among others had equipped the decentralized facilities for treating sewage and municipal solid waste.

Second, co-treatment of waste is feasible. As an example, organic waste with high moisture content could be co-digested with sludge and faeces, and has a high recycling potential for energy and biomass (Mata-Alvarez et al., 2000). There is a trend toward using larger and sophisticated co-digesting systems with better process controls that could generate electricity in China (Lusk, September 1998). Other research also shows that decentralized co-digestion of faeces and organic solid waste is also available (Chen et al., 2005). Urban community equipped with alternative urine diversion dry toilet (UDDT) and waste co-compost facilities were built up and demonstrated as much as possible in Ordos, Inner Mongolia, which is located in our study area (Sun et al., 2006).

Last, ecosan systems with low-cost and high potential of conserving water and reclaiming nutrients are a priority to the poor, dry, and barren Loess Plateau region. Comparatively expensive technologies, such as incineration of municipal solid waste, were not put into the matrix with the consideration of economic feasibility.

We integrated eight ecosan systems according to the analysis of technical feasibility and applicability (see Table 1).

2.2. Material flow analysis

Material flow of GHGs, water pollutants, nutrients, and capital and running cost were considered. An input and output inventory of the materials, energy, and money was developed using LCA and cost benefit analysis (CBA): (1) input: food waste, faeces, urine, grey water, electricity, gasoline, and capital and running cost; (2) output: methane, carbon dioxide, BOD₅, SS, NH₃-N, nutrients (N, P, K), and income. The details of these methods are shown in Appendix A.

2.3. Benefit assessment

2.3.1. Theoretical framework

Urban ecosan is a kind of social–economic–natural complex ecological system (Ma and Wang, 1984); the structure and the function of the ecosan system are shown in Fig. 2. The ecological-economic assessment includes the following factors:

- (1) Natural factor: global warming and regional eco-service. The maximum, minimum, and average values of GHGs, water pollutants, and nutrients reclaimed for food production (see Appendix A) were calculated.
- (2) Social factor: human health and employment opportunities. Direct and indirect impacts on human health were studied and the increase of direct employment opportunity was analyzed.

- (3) Economic factor: capital cost, running cost and benefits, benefits includes:

- Recycle of methane, which was assumed to convert to electricity and the cost of the electricity generator was subtracted from the benefit.
- Reduction of methane emission, the benefit was calculated under the current carbon exchanging market through the clean development mechanism (CDM), about 8 USD/t CO₂e.
- Reclaimed water, the capital cost of facilities, pipes, and the running cost of reclaiming processes were subtracted from the benefit.
- Reclaimed nutrients, the nutrients were converted to total N, P₂O₅, K₂O equivalents, and the benefits were based on the current fertilizer price.

2.3.2. Scenario design

- (1) Traditional centralized treatment (CT): C1 was applied. Solid waste, faeces, and sewage were centralized treated under the end-of-pipe model and the nutrients, energy, and water were not recycled.
- (2) Centralized ecosan (CE): C2–C4 were applied. Solid waste, faeces, and sewage were centralized treated under the ecosan model, and the nutrients, energy, and water were recycled as much as possible.
- (3) Decentralize and centralize mixed ecosan (ME): C2–C4 and D1–D4 were applied. Centralized ecosan technologies were

Fig. 1. The study area and distribution of ecosan demand in China.

applied at already built urban areas, while decentralized technologies were applied at newly built urban areas.

3. Results and analysis

3.1. Current sanitary system

We investigated the urban sanitary systems of typical Loess Plateau cities, such as Taiyuan, Xi'an, Lanzhou, and Yinchuan. We found that the cities had poor sanitation and the existing sanitary

systems were centralized and similar among cities (see Fig. 3). The characteristics of the current system were as follows:

- Fourteen Tg of solid waste (organic fraction was about 50%) was generated, while only 39% of them was treated harmlessly and 86% of them was disposed in 44 landfill facilities (National Bureau of Statistics of China, 1999–2006). Landfills in many cities were poorly designed and engineered. The compost was of low quality because of the out-of-date equipment and lack of source separation (Wang and Nie, 2001).

Table 1

Ecosan systems by integrating sanitary technologies.

ID	Integrating sanitary technologies	Classification
C1	Solid waste centralized landfill (with no landfill gas recycling facilities) Faeces and urine are flushed and treated with grey water (with no sludge compressing and reclaiming facilities)	Centralized
C2	Solid waste centralized landfill (with landfill gas recycling facilities) Faeces and urine are flushed and treated with grey water (with sludge compressing and reclaiming facilities)	Centralized
C3	Food waste, faeces, and urine (flush toilet) centralized digest Grey water centralized treated	Centralized
C4	Food waste centralized compost Faeces and urine (flush toilet) centralized digest Grey water centralized treated	Centralized
D1	Food waste and faeces (dry toilet) decentralized compost Urine decentralized storage and recycle Grey water decentralized treated	Decentralized
D2	Food waste, faeces, and urine (flush toilet) decentralized digest Grey water decentralized treated	Decentralized
D3	Food waste and faeces (flush toilet) decentralized digest Urine decentralized storage and recycle Grey water decentralized treated	Decentralized
D4	Food waste decentralized compost Faeces (flush toilet) decentralized digest Urine decentralized storage and recycle Grey water decentralized treated	Decentralized

Fig. 2. The structure and functions of an ecosan system.

- Most faeces produced by the residential districts were discharged to the sewer pipe system. Faecal residues discharged from public toilets (about 3.4 million/year) were collected and 37% of them were treated in faecal treatment plants; otherwise, they were directly reclaimed to the farmland.
- Twenty-nine cities lack sewage treatment plants (about 57%). Thirty-three percent of wastewater was treated in centralized plants and about 60% of sludge had low quality.

The natural and social conditions of Loess Plateau made the sanitary problems even serious:

- Lack of water: surface water, ground water, and rainwater were only 37%, 62%, and 39% of the national average, respectively (National Bureau of Statistics of China, 1999–2006).
- Less developed: the average gross domestic product (GDP) was only 63% of the national average (National Bureau of Statistics of China, 1999–2006).

In this region, the farm land was barren and the organic matter in soils was below 1% (Institute of Soil Science CAS, 1986), the nutrient demands for farming were huge.

A comprehensive index integrating the factors of average water resource, arable farmland, and average GDP was set to study the distribution of ecosan demand in China (see Fig. 1). We found that the index of the study area is the lowest among all the regions in China.

3.2. Material, energy, and money flow of ecosan technical systems

Table 2 shows the material, energy, and money flow of ecosan systems.

3.3. Natural assessment

3.3.1. Global climate impacts

The emission of GHGs is shown in Fig. 4. If no reduction measures are taken, 9.89 Tg of GHGs will be released (CT, year 2030). If 80% methane produced by the solid waste landfill and 60% methane produced by the treatment of sludge were recycled, total emission of GHGs could be reduced to 1.13 Tg of carbon dioxide equivalent (CO₂e)/year (CE, year 2030). ME releases less GHGs, only 0.82 Tg/year (year 2030), because decentralized ecosan systems consumed less gasoline and electricity. If the decentralized anaerobic digest is applied and methane is maximally recycled, the GHGs emission could reduce to 0.32 Tg, which was only 3.2% of CT (ME, C3 and D3, year 2030). Fig. 5 shows that the methane recycling potential of CE and ME is at the same level, and

Fig. 3. Sanitary system of Middle West cities under the end-of-pipe technical model. The unit of the figure is Gg, the data were based on the year 2003 (Ministry of Construction of China, 2004).

Table 2Material and money flow of ecosan systems (per 10³ capita).

Ecosan systems	GHGs (Mg/year)		Water pollutants (Mg/year)			Nutrients reclaiming potential (Mg/year)			Capital & Running cost, thousands (RMB/year) ^a		
	CH ₄ recycle	CO ₂ e emission	BOD ₅	SS	NH ₃ -N	N	P	K	Capital cost	Running cost	Sum
C1	0.00	4150.13	10.99	11.00	9.13	0.35	0.08	0.35	346.3	386.7	733.0
C2	148.04	1041.21	10.99	11.00	9.13	0.35	0.08	0.35	346.3	386.7	733.0
C3	159.52	177.52	11.01	11.01	9.17	12.29	2.07	3.57	392.0	418.5	810.5
C4	4.38	198.65	10.95	10.95	9.13	12.29	2.07	3.57	361.6	395.1	756.7
D1	0.00	45.00	5.55	2.77	2.77	48.16	7.48	13.40	88.8	179.3	268.1
D2	164.24	32.85	7.30	3.65	3.65	13.92	2.96	5.20	141.5	240.3	381.8
D3	162.43	26.94	5.99	2.99	2.99	47.52	7.16	12.76	184.0	267.7	451.7
D4	7.29	47.96	7.30	3.65	3.65	7.52	2.16	3.76	173.8	303.1	476.9

^a 1 RMB=0.133 USD.

integration of C3 and D2 could reuse maximum methane, 0.038 Tg (year 2030).

3.3.2. Regional eco-service

(1) Water pollution:

Water pollutants emissions (BOD₅) of CT, CE, and ME are shown in Fig. 6. We found that the BOD₅ emission of CT and CE is almost the same, and the value of CE fluctuates slightly because the centralized terminal is a two-stage wastewater plant, which has a limitation of effluent quality. ME releases less BOD₅ than CT and CE (88%) since the grey water is separated at the source and the difficulty of wastewater treatment is decreased. D1 applies the technology of UDDT and emits only 0.55 Mg of BOD₅ per 1000 people/year, which was the minimum of all ecosan systems.

Fig. 4. GHGs emissions of different ecosan developing models. **Fig. 5.** GHGs reduction of different ecosan developing models. **Fig. 6.** BOD₅ emissions to water bodies of different ecosan developing models.

(2) Nutrients:

Nutrient recycling fluctuates obviously with different ecosan technologies. It seems that decentralized ecosan systems could recycle more nutrients. For example, D1 could recycle maximum nutrients of 4.816, 0.748, and 1.340 Mg of N, P, and K per 1000 people/year, respectively (see Table 2). Landfill of organic solid waste is the main reason of nutrients loss. For example, C1 and C2 could recycle 0.035 Mg of nitrogen per 1000 people/year, which is only 2.8% of C3.

Increased food production attributed to nutrients reclaim is shown in Fig. 7. On the average, CT, CE, and ME could produce 32.1, 461.4, and 809.9 Gg of foods, respectively (year 2030). Reclaiming nutrients are important for Loess Plateau area, because the bearing capacity of local farmland has already overloaded three million people in the year 2005 (Chen et al., 1991). Chemical fertilizer was over applied to farmlands to increase food production; the fertilizer application rate may reach 300 kg/ha (year 2030), which

Fig. 7. Food production increase of different ecosan developing models.

Fig. 8. Mutual health impacts between urban and rural areas.

is higher than 150–225 kg/ha, the critical application rate of high leaching and runoff risk (Norse, 2003).

Another interesting finding is that the maximum nutrient recycling from urban sanitary system is 16% of the total nutrient consumption. CE and ME could recycle 0.7–44.2 Gg/year of nitrogen through urban ecosan system, while the fertilizer demand of nitrogen will reach 282 Gg/year. Assuming that 10% nutrients were assimilated and respirationally exhausted by human beings, then at least 74% of nitrogen may be lost on the agricultural processes, such as by-products of cereal waste and loss by the flush of rain, hence, the recycling of agricultural waste and conservation of farmland are also important.

3.4. Social assessment

3.4.1. Human health

Fig. 8 shows the mutual health impact between urban and rural areas. Most rural people do not have centralized freshwater supply, as a result the health risk may be higher. Xu et al. (2003) found that, in the rural areas, the region prevailing with esophageal cancer definitely has excess nitrate in the ground water, which was caused by sewage and chemical fertilizer. We know from the former analysis that (1) water pollutant emission: CT > CE > ME; (2) chemical fertilizer reduction through reclaim of nutrients: ME > CE > CT. Although the exact quantitative relationships among human health, sewage, and fertilizer were not determined, we could establish the sequence of rural health risks, which were affected by the urban sanitary systems: CT > CE > ME. But we should realize that nutrients reclaim need strictly observe the WHO guidelines (WHO, 2006).

3.4.2. Employment opportunity

Ecosan could add industries and extend the entire industrial chain of sanitary systems, including the industry of logistics, community management, organic fertilizer production, urban agriculture and forestry, technical consultants and services, and others. The increase of employment opportunity is difficult to evaluate quantitatively, although the direct increase of employment of sanitary systems could be estimated, about 1–2 per thousand people to service the process of segregation, recycling, and maintenance and running the facilities. About 2% of people in the studied cities are picking up solid waste for a living; they could be trained to service the ecosan systems.

Fig. 9. The comprehensive cost-benefits of different ecosan developing models.

3.5. Economic assessment

Cost and benefit analysis of CT, CE, and ME is shown in Fig. 9: (1) CT, the capital, and running cost are increased with the subsequent increase of urban population and the benefit is comparatively less than the cost. Only 5.92–7.17 million RMB benefited by the production of fertilizer, was 0.4% of the cost; (2) CE, the capital, and running cost were 4.6% more than CT, except that its potential benefits were higher. When the benefit was taken into account, the net cost was 10% of CT; and (3) ME, the capital, and running cost were the least, about 89% and 85% of CT and CE, as the transport system (vehicles and wastewater pipe networks) of the decentralized ecosan costs less than the centralized. The benefits of ME were 253 and 1.1 times higher than CT and CE, when the benefits were taken into account, net cost of sanitation turned into net benefits, about 267 million RMB/year.

If all wastewater, faeces, and solid waste were harmlessly transferred and treated in the traditional centralized way (CT) in the year 2010, 1.43 billion RMB will be needed for capital and running cost. In the year 2003, there was only an expenditure of 0.31 billion RMB/year for the treatment of wastewater and solid waste. If this expenditure increases 10%/year, a gap of 0.83 billion also exists. The unit increase is 0.95 RMB/Mg of sewage and 8 RMB/year per capita for treatment of solid waste. If we are seeking for technical innovation of ecosan, for instance, the centralized ecosan system (CE) only needs 0.15 billion RMB, while ME could even produce 0.22 billion RMB of net income.

Additionally, clean development mechanism (CDM) was an international cooperation method that was built based on the *Kyoto Protocol*. It could aid developing countries with the investment of projects that prevent global warming. If ecosan were developed in the studied area, from the year 2010 to 2030, 0.203–0.248 (CE) and 0.176–0.215 (ME) Tg of methane/year could be recycled. According to the current carbon market (8\$/Mg CO₂e), there were potential benefits of 0.25–0.31 billion RMB of Chinese Loess Plateau cities through CDM operation. This benefit is 35% of the capital cost of an ecosan system (sewage, faeces, and solid waste treatment facilities, supporting system for pipes, and transferring vehicles and stations). Therefore, the CDM could be used to ensure the startup investment of ecosan systems.

4. Conclusion and discussion

Ecosan systems have the following impacts and benefits: (1) Both centralized and decentralized ecosan systems reduce GHGs and are helpful for preventing global warming. Decentralized ecosan systems reduce more water pollutants

than centralized systems, while ecosan systems reclaim more nutrients than the traditional system. Thus, ecosan systems have better function of regional eco-service. (2) Ecosan systems have important social impact by reducing the risk of human health and increase employment opportunity. (3) Ecosan systems produce considerable incomes and make the system works sustainable.

Conversely, there are some bottlenecks in developing urban ecosan: (1) lack of policies, legislations, and standards; (2) lack of systems of production, construction, and services; (3) lack of startup investment of research and construction; (4) lack of human resources of management and research and development; (5) lack of education and propaganda. CDM could help developing countries to apply advanced technologies and obtain startup investments, but other compensating mechanisms still need further research. Relative policies and regulations should be developed, such as landfill restriction of unpretreated organic solid waste, charging fees of household wastewater and solid waste, financial subsidies of recycling water and organic waste, and national guidelines on the safe use of reclaimed nutrients. Regional differences and public demands should be respected when developing ecosan projects.

This paper has established a framework for the ecological-economic assessment for understanding and controlling the complexity of ecosan development, further research regarding assessing methodologies still need to be conducted to provide evidences and reasons for determinating compensation policies and financial supports.

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Appendix A. Material and money flow of integrated ecosan technical systems

A.1. GHGs emission and reduction

The sources of GHGs included : solid waste landfill digest and transfer; faeces and urine digest; sludge digest, etc. The calculations were based on the methodologies of the United Nations Framework of Convention on Climate Change (IPCC, 2000, 2001). The carbon dioxide emission from biomass anaerobic decay and aerobic treatment processes was considered GHGs neutral according to the UNFCCC methodology, the carbon dioxide emission from combustion of fossil fuel and grid electricity, emitted by transportation and auxiliary equipments was included (UNFCCC/CCNUCC, 2006). The parameters were based on the data of local investigations and statistics. If there were no available data to be applied, we used the experiential default values for Asian developing countries recommended by ICPP and UNFCCC, or the data reported by relative references.

A.2. Water pollutants

Water pollutants included BOD₅, NH₃-N, and SS. The sources of water pollutants emission were : landfill leachate treatment plants, faeces treatment plants, and decentralized and centralized wastewater treatment plants. In China, emitted wastewater from such

sources should reach the second-grade level, which was regulated in the integrated wastewater discharge standard (GB 8978-1996). Therefore, we assumed that the quality of emitted wastewater from such sources was: 30 mg L⁻¹, 30 mg L⁻¹, 25 mg L⁻¹ for BOD₅, NH₃-N, and SS, respectively. Consequently, there were no similar national standard to evaluate the quality of emissions of decentralized grey water treatment facilities. As a result, we studied many cases of constructed wetland and evaluated by an estimate value of case studies (Lens et al., 2001), which were 20 mg L⁻¹, 10 mg L⁻¹, 10 mg L⁻¹ for BOD₅, NH₃-N, and SS, respectively.

A.3. Nutrients

Nutrients included were nitrogen (N), phosphorus (P), and kalium (K). The sources of potential recyclable nutrients included food waste, faeces, urine, and grey water. The characteristics (N, P, K contents) of solid waste, faeces, urine, and grey water were based on former studies (Tchobanoglous et al., 2000; Wang and Nie, 2001; Lens et al., 2001).

A.4. Capital and running cost

- Capital cost included treatment plants or facilities of solid waste, faeces, urine, and grey water; vehicles and facilities for the transportation of solid waste; pipes, etc. The capital costs of inhabiting buildings and facilities of households were not included. We assumed that annual capital cost was one tenth of the total capital cost.
- Running cost included treatment cost of plants or facilities, cost of vehicles, labors, etc. However, maintenance of household facilities was not included.
- The Chinese Ministry of Construction has issued a series standards of constructing projects' economic evaluation, including landfill, compost, digestion, and wastewater treatment projects (Ministry of Construction of China, 1996, 2001). If there are no available standards, we referred to the similar projects in China.

A.5. Increased food production

The increased food production, attributed to the reclaimed nutrients of ecosan systems, was calculated based on the farmland productivity of different provinces. The formula was as follows:

$$Y_{i,j} = Y_{0,i,j} \cdot \sqrt[3]{\frac{X_N}{X_{N0}} \cdot \frac{X_P}{X_{P0}} \cdot \frac{X_K}{X_{K0}}} \quad (2)$$

where

$Y_{i,j}$ is the increased food production attributed to the reclaimed nutrients;
 i is the year;
 j is the province;
 $Y_{0,i,j}$ is the predicted food production (affected by such factors: the soil condition, potential sunlight, accumulated temperature, productive capacity, irrigation capacity, and fertilizer demands);
 X_N , X_P , and X_K are the reclaimed nitrogen, phosphorus, and kalium, which are converted to the equivalent of N, P₂O₅, and K₂O, respectively;
 X_{N0} , X_{P0} , and X_{K0} are the demanded nitrogen, phosphorus, and kalium for Y_{max} , which are converted to the equivalents of N, P₂O₅, and K₂O, respectively.

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