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Improving sewage sludge treatment and utilisation in China: a German perspective on barriers to and measures for the dissemination of innovative technologies

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ABSTRACT

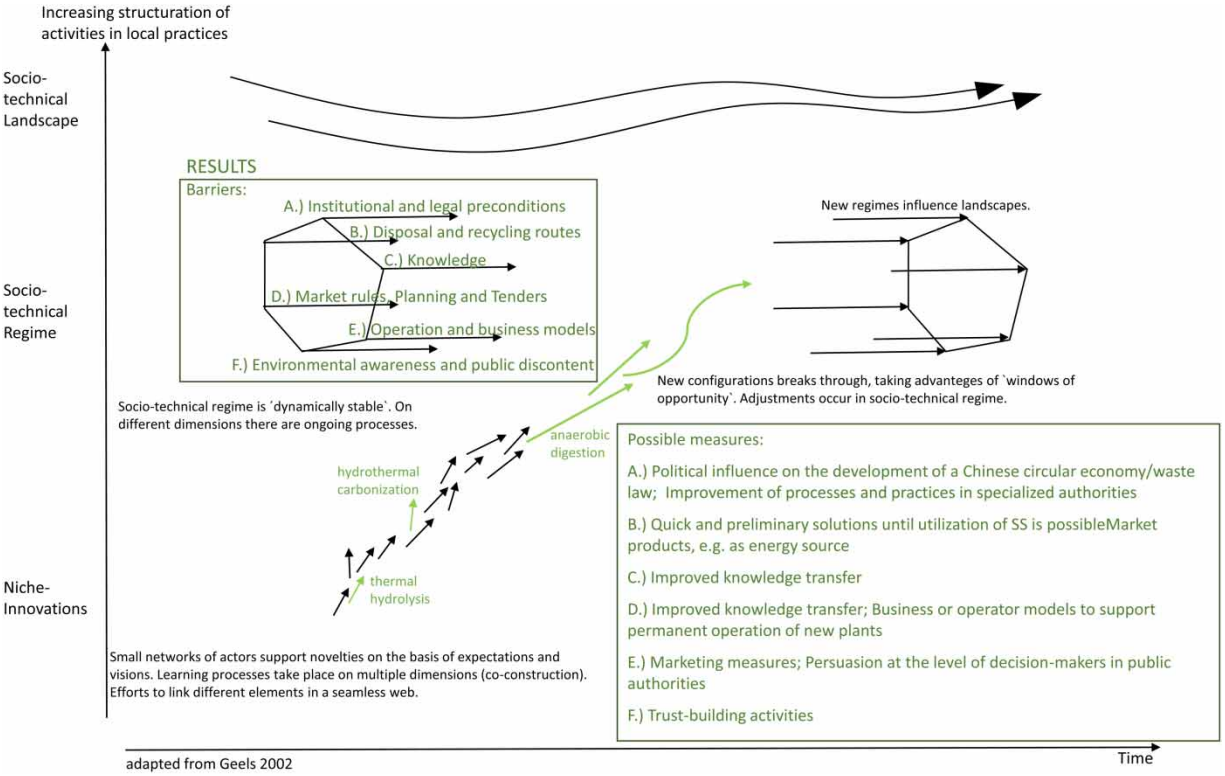
In China, there is enormous development potential for resource recovery from sewage sludge. Government plans indicate that there will be greater investment in sewage sludge treatment, recycling and associated new technologies. Expert interviews and an expert workshop with representatives of German firms and institutions were held in order to identify barriers to and possible measures for the dissemination of technologies geared towards the utilisation of sewage sludge, such as anaerobic digestion, thermal hydrolysis and hydrothermal carbonisation. The following measures were identified as crucial: influence and support for the development of suitable regulations for sewage sludge in China, improvement in the processes and practices within specialised authorities, improved knowledge transfer, the development of appropriate business or operator models and persuasion of decision-makers within public authorities. German companies cannot implement most of these measures easily.

Key words: anaerobic digestion, hydrothermal carbonisation, institutional barriers, resource recovery, socio-technical innovation, thermal hydrolysis

HIGHLIGHTS

- For business development, it is crucial to have strong ties with Chinese partners.
- Operator models require great commitment and most of the German companies are not suitable due to their size or ownership structure.
- Transition school literature was helpful to develop an understanding of barriers and measures concerning resource-efficient handling of sewage sludge in China.

GRAPHICAL ABSTRACT



INTRODUCTION

With rising urbanisation and the expansion of the wastewater infrastructure in China, an increasing amount of sewage sludge is being produced. So far, investments and political attention concerning the wastewater sector have focused on wastewater treatment technologies, with little attention paid to the disposal of sewage sludge. In 2013, over six million tonnes of sewage sludge (dry matter) were produced, of which only 20% was disposed of safely, mainly in landfills or through land application, for example for agriculture or landscaping (Yang *et al.* 2015). Statistics from the Ministry of Housing and Urban-Rural Development of the People's Republic of China indicate that there has been progress in sewage sludge disposal in recent years. In 2019, 27% of the sewage sludge was incinerated, while landfilling and land application accounted for 49% (Wei *et al.* 2020). Sewage sludge treatment, including new technologies for resource-efficient recycling, is also applied. In 2019, seven tonnes per day were treated by anaerobic digestion (AD) and eight tonnes per day by thermal hydrolysis (THP), together accounting for 0.04% of the total amount of sewage sludge produced (cf. Wei *et al.* 2020). There is still an urgent need for proper disposal of sewage sludge (Lu *et al.* 2019) and thus also great potential to establish sewage sludge recycling in a resource-efficient way in order to reduce secondary pollution (Jiang 2020) and CO_2 emissions (Wei *et al.* 2020).

In addition to AD, new treatment technologies for resource-efficient sewage sludge utilisation are THP and hydrothermal carbonisation (HTC). All three treatment technologies achieve resource recovery, such as fuel for energy production, agricultural products or both. All three require a certain quality of sewage sludge, high initial investments for the construction of the plants, skilled staff for operations, as well as the marketing and distribution of recycling products. The situation with regard to AD in China is known from the literature, which contributes to an understanding of the challenges around the dissemination of other treatment technologies. Problems with the anaerobic treatment of sewage sludge are caused by the poor conditions of the sewer networks, especially sand and extraneous water entry, and by the existing wastewater treatment plants, which were not designed for resource recovery (Yang *et al.* 2015). In recent years, the construction and modernisation of the wastewater infrastructure have been promoted in Five-Year Plans, which are national economic planning tools. According to the 13th Five-Year Plan (2015–2020), 55 and 34% of the total investment in the wastewater infrastructure will be allocated to the sewer network and wastewater treatment plants, respectively, while 5% will

be allocated to sewage sludge disposal (cf. Viklenko 2017). Investment decisions about sewage sludge treatment and disposal are also hampered by a lack of information about financing and tariff allocation (German Industry & Commerce Greater China 2019b), all of which have a negative impact on the development of the market for sewage sludge treatment (Yang *et al.* 2015). Moreover, there are no consistent standards or regulations for sewage sludge disposal (German Industry & Commerce Greater China 2019b). The Ministry of Housing and Urban-Rural Development is responsible for legislation on sewage sludge treatment and disposal and is the main actor among the five ministries that set out legal requirements. Provinces and municipalities have to implement the laws and environmental regulations issued by the ministries, which compete with other regional goals such as economic growth (Morscheck *et al.* 2018). The Chamber of foreign Commerce for German companies issued extensive documents concerning the Chinese wastewater infrastructure that also include a description of market conditions. There is significant competition in the Chinese wastewater sector among national, state-owned and foreign companies and high price pressure (German Industry & Commerce Greater China 2018), while business relationships and contacts play an extremely important role (German Industry & Commerce Greater China 2019b). At the same time, calls for tender are not visible to German companies and the whole process is opaque (German Industry & Commerce Greater China 2019a). According to a literature review undertaken by Froese *et al.* (2019) focusing on the challenges faced by multinational enterprises in China, government procedures are generally not transparent and the business environment has become increasingly difficult with legal, regulatory and governmental challenges. Furthermore, domestic legal, regulatory and government interventions seem to be used to benefit domestic companies (ibid). Zimmermann *et al.* (in preparation) present the barriers to and measures for the resource-efficient treatment and utilisation of sewage sludge using the example of AD based on interviews with representatives of Chinese firms and institutions. Out of eight measures, the two considered most efficient are more government support (e.g. openness and subsidies) and clearer regulations and standards.

Resource-efficient utilisation of sewage sludge is not just a question of efficient treatment technologies but requires certain preconditions in order for them to be disseminated and function well in the long run. However, how can companies offering treatment technology cope with these additional challenges? The main questions addressed in this research were: What are the barriers to resource-efficient handling of sewage sludge in China and which measures can be taken to address these?

METHODS

The conceptual framework used in this research was the multi-level perspective developed in transition school literature. The multi-level perspective refers to three levels that influence socio-technical innovations: the landscape, the regime and the niche (Geels 2002). While the landscape represents global trends influencing the regime and niche of innovation, the regime represents the prevailing system. The niche is a space protected from the prevailing forces where innovations often start to develop. Transition school aims to understand the processes of transitions, for instance, by analysing historical cases of the dissemination of innovations. It commenced in the field of cleaner technology but now aims to look at entire systems of production and consumption, with a particular focus on sustainable development (Smith *et al.* 2010). Topics are often linked to new and resource-efficient approaches dealing with food, energy, water supply and transport. These are areas where, alongside technological innovation, social and institutional innovations play an important role. In 2012, Smith and Raven published a paper focusing on the protection of niches and gave a full picture of the socio-technical dimensions of the regime discussed in transition school. These dimensions are industry structure, technologies and infrastructure, knowledge base, markets and dominant user practices, public policy and political power, and cultural significance. These six dimensions were used as a starting point to frame the scope of the present research.

Our research comprised three different methods: desk research, expert interviews and an expert workshop (see Table 1). Expert interviews and the workshop were aimed at acquiring an in-depth understanding of the situation in China from the perspective of German companies and institutions with experience in the Chinese water and disposal sector. Focusing on the barriers connected to resource-efficient sewage sludge disposal, the objective was to identify and develop measures to overcome these barriers and ultimately to formulate recommendations. Expert interviews allow expert knowledge specifically to be acquired (Meuser & Nagel 2009). This instrument is suitable for data collection as the questions could be addressed in interviews with representatives of German companies from relevant industries and related institutions. For the structure of the qualitative content analysis according to Mayring (1991), the six dimensions presented by Smith & Raven (2012) were used.

Table 1 | Summary of methods, topics and planned output of the research

Method	Literature review	Expert interviews	Expert workshop
Topics	– Policy documents: sewage sludge standards, 'Five-Year Plans' – Current situation – Transition School literature	– Industry structure – Infrastructure – Policy and political power – Market and end user – Knowledge – Cultural significance	Discussion of measures for improved sewage sludge handling in China
Planned output	Preparation for the interviews and the expert workshop, support of data analysis and development of measures	Detailed understanding of barriers and measures for improved sewage sludge handling in China	Formulation of recommendations

The research process, explained in detail in this paragraph, began with the literature review, which continued throughout the research, while the expert workshop validated, complemented and disseminated to the experts the results of the expert interviews. First, desk research was undertaken in a review of English, German and Chinese literature and internet sources. Here, sources such as Chinese policy documents, workshop proceedings on the wastewater infrastructure in China and scientific literature were consulted. In total, 20 expert interviews were conducted with managing directors and employees of German companies as well as with representatives from research institutions, the financial sector and the German Chamber of Foreign Trade. Many of the experts have a background in civil, environmental, process or chemical engineering and work in the field of water and wastewater treatment technologies. Of the 20 experts interviewed, seven were of Chinese origin. The other interviewees were selected due to their extensive experience of working in China. The semi-structured, guided interviews were mostly conducted over the telephone. Ideas for measures given by the experts or developed by the research team were collected and then discussed in subsequent interviews and with the project partners. The analysis of the interviews and the development of the measures were accompanied by further research of Chinese, German and English online sources. Finally, the transcripts were analysed in a deductive manner according to the criteria of qualitative content analysis using the six dimensions mentioned above. These preliminary results – the barriers to and measures for improved handling of sewage sludge in China – were presented and discussed during an online workshop with five experts. The experts invited to the workshop had previously been interviewed. They were selected for their extensive knowledge and wide understanding of the challenges being faced and the suitability of the measures proposed. Four experts were representatives of German companies, while two of them were of Chinese origin. One expert worked in science. Two online queries and a shared screen for structuring the discussion, comparable to a flip chart, supported the workshop. Furthermore, the discussion and results were documented in written minutes. This documentation was used to complement the results from the interviews.

RESULTS AND DISCUSSION

Policy and political power

This dimension includes legal and institutional preconditions. China's legislation on sewage sludge, which is similar to Germany's, is too strict for the conditions in China, and little consideration is given to important qualitative and quantitative aspects, such as soil quality (pH values) and volumes for soil application. Moreover, there are contradictions in the legislation on fertilisers with regard to agricultural utilisation (see the next section). The national legislation sets minimum requirements that are specified further at a provincial level. Since the legal requirements are often difficult to meet, other solutions need to be found. According to the experts, the authorities are often open to pragmatic solutions or legal requirements are not monitored at all.

However, legal requirements should serve as guidelines for operations and offer a framework for plant operators. The development of suitable legal standards and framework conditions for the handling of sewage sludge in China can be assisted by German-Chinese or European-Chinese cooperation arrangements. Cooperation already exists, for instance, European-Chinese working groups at the European Union Chamber of Commerce in China (EU-Chamber). The German Society for International Cooperation (GIZ) also provides

policy advice in an international context based on specific projects. However, its focus is only on basic services and technologies when it comes to infrastructure. Moreover, the dissemination of technologies can be supported by international research projects when Chinese project partners present promising technologies to decision-makers.

Institutional frameworks and fees for sewage sludge disposal also appear unclear. According to the interviews with representatives of German companies, local responsibility for sewage sludge disposal is not clearly defined. In some cases, the local government or municipal actors are responsible; this can be the water, the building or the environmental authorities. In other instances, the operator of a wastewater treatment plant is responsible for sewage sludge disposal. The example of Qingdao (Qingdao NDRC 2021) shows how the responsibility was transferred to the operator of a wastewater treatment plant with the payment of an additional fee. The water and wastewater fee are often insufficient for the proper disposal of sewage sludge. An additional fee of this kind can be determined in a public hearing; the local government is then responsible for balancing the costs. Again, this is not in agreement with information obtained during interviews with the experts from Chinese firms and institutions, according to whom the government covers the cost of sewage sludge transport and disposal, while the operator is only responsible for dewatering (Zimmermann *et al.* in preparation).

Infrastructure

This dimension is concerned with the different disposal and utilisation routes and includes the treatment of sewage sludge for improved utilisation. The development of infrastructures is strongly linked to politics and investment planning in the Five-Year Plans. Anaerobic treatment of sewage sludge was specified in an earlier Five-Year Plan; however, only a small number of plants have been constructed and only a small proportion of the digesters originally built are still in operation. Here, the experts are divided, with some acknowledging the suitability of AD while others do not. The main issues mentioned refer to the wastewater infrastructure (see Introduction). Other problems raised during the interviews are the diet in China, safety issues and energy subsidies. According to one expert, the diet in many parts of China is plant-based, which has a negative effect on the chemical oxygen demand (COD) of the sewage sludge since plant oils are dissolved in the liquid phase. Further desk research showed that meat consumption in China has increased greatly in the past 20 years and is now approximately 50 kg per capita and year, which is close to Germany's meat consumption of approximately 60 kg per capita and year (Chemnitz & Wenz 2021). Moreover, safety concerns were mentioned by most of the experts. Explosions are the reason why AD has a poor reputation. Finally, energy production from methane is not economically viable due to energy subsidies. The representatives of Chinese companies and institutions also mentioned these barriers but also stated that the final utilisation of the fermentation residues remains unclear since agricultural use is prohibited and sewage sludge is not well suited for incineration after AD due to the reduction of carbon (Zimmermann *et al.* in preparation). Those in favour of AD of sewage sludge in China argue that a lot has been invested in recent years to modernise the wastewater infrastructure, with the result that suitable preconditions for anaerobic treatment have been created in many places. Moreover, AD is specified for sewage sludge treatment in the 14th Five-Year Plan (2021–2025) and, according to one expert, energy production from renewable sources is now being promoted under new government plans.

Landfilling of sewage sludge is one of the main disposal routes and often includes long-distance transportation from urban to rural regions. According to the 13th Five-Year Plan (2016–2020), sewage sludge needs to be dewatered for landfilling. The solid content must constitute at least 40%. In some provinces, this has already been increased to 60%. According to the 14th Five-Year Plan, the number of landfills for sewage sludge in urban regions needs to be rapidly reduced. In addition, since the law already stipulates an organic content of 5%, i.e. ash from burned sewage sludge only, landfilling of sewage sludge will probably be banned entirely.

Many experts consider incineration to be the best means of disposal. The importance of other treatment steps for safe and efficient resource recovery prior to incineration was highlighted. According to the current Five-Year Plan, centralised sludge incineration is to be promoted. Two problems were identified here: insufficient incineration capacities and the difficulty of finding sites on which to build new incineration plants (see the section Cultural Significance).

Soil applications such as in farming, forestry and landscaping are currently important disposal pathways. If produced for domestic use only, experts consider the agricultural utilisation of sewage sludge suitable for rural areas. However, there are legal barriers to this. According to the new fertiliser regulation, fertilisers made from sewage sludge cannot be marketed; the sale of recycling products as soil conditioners is only allowed with a certificate,

which, according to one expert, is probably hard to obtain for wastewater treatment plant operators. Thus, although the use of sewage sludge in agriculture is permitted, according to the legal standards for sewage sludge, its sale is prevented by fertiliser legislation. The experts did not consider landscaping and forestry to be suitable areas for sewage sludge disposal.

According to the Ministry of Construction (Wei *et al.* 2020), the use of sewage sludge for construction material in 2019 was more than 15%. The interview partners found this difficult to assess and were unable to report on this from their own experience. However, the pollutant load and possible acceptance problems were seen as potential barriers. According to a life cycle assessment, its use in the production of bricks and building materials has the lowest environmental impact compared with incineration and thermal utilisation or AD and biomass utilisation (Zhang & Matsumoto 2021). Especially in areas where the use of fluvial sands is prohibited, ash from incinerated sewage sludge is used to make bricks (Zimmermann et al. in preparation). The experts from Chinese companies and institutions also pointed out this particular usage as safe and assumed the least public concerns compared with other recycling products (ibid.).

THP is a treatment technique that is already in use in China due to marketing by a Swedish company. Possible utilisation routes linked to this treatment step are agricultural utilisation and energy production if AD is applied after THP. The 14th Five-Year Plan specifies THP as a suitable treatment for the utilisation of sewage sludge.

Measures for improved handling of sewage sludge in relation to the various disposal and recovery routes involve increasing the incineration capacities and developing and marketing high-quality sewage sludge recycling products. A possible preliminary mitigation measure is the stabilisation of sewage sludge and the reduction of volume for safe storage until recovery capacities are developed, for example, by HTC. Alongside the often-problematic construction of new incineration plants (see the Cultural Significance section), co-incineration capacities can also increase thermal sewage sludge utilisation. In waste incineration plants, co-incineration of sewage sludge is limited to 5–10% co-firing. However, those capacities should be re-evaluated. The reason for this is the change in the composition of comingled waste: kitchen waste has been reduced due to an increase in waste separation. Moreover, the fraction of plastic waste is increasing due to a reduction in informal collection. These developments might result in a rise in co-incineration capacities. However, as the example of co-incineration in the cement industry shows, this can also have negative consequences. After being promoted through respective policy measures in recent years, its economic and environmental impacts are not always satisfactory because of different construction methods and different sludge characteristics (Xu *et al.* 2019). HTC and THP are two treatment technologies that can transform sewage sludge into high-quality recycling products for biomass, energy production and thermal utilisation. Such recycling products need promotion and marketing or other ways to link together the various actors in the value chain in order to establish profitable business models. Experts from the Chinese firms and institutions also confirmed that final disposal of the solids after HTC has yet to be established (Zimmermann *et al.* in preparation).

Knowledge

This dimension is concerned with the dissemination of information, professional knowledge and knowledge transfer. According to the experts, there are different opinions on sewage sludge treatment in China and competing networks at different universities, resulting in a wide variety of treatment technologies being in use. There is a lack of knowledge especially within the specialised authorities, while the results of Zimmermann *et al.* (in preparation) also point out that these knowledge gaps exist particularly when it comes to new technologies such as HTC and THP and are frequently found among older experts and decision-makers who do not have access to English literature. Apart from that, solutions are often ordered from above, which leads to unworkable requirements. On technical boards, instead of expert discussions taking place, consensus is worked out in advance. At treatment plants, it is difficult to address malfunctions and design errors in the communication between the plant operator and the Local Design Institutes responsible for design and construction. Engineers working at the Design Institutes are aware of problems due to outdated standards but are not in a position to ignore those standards.

The industrial association comparable to the German Association for Water, Wastewater and Waste (DWA), an important factor for exchanges within the professional community and technical literature, is the CUWA (China Urban Water Association). According to the experts from German companies and institutions, Chinese associations are more like interest groups. Events organised by the CUWA are often used for the promotion of products because speakers have to pay to give presentations. Interestingly, this is perceived quite differently by

the experts from the Chinese firms and institutions, who emphasised good communication and expressed their appreciation for the varied events organised by the CUWA (Zimmermann *et al.* in preparation).

In order to improve knowledge transfer, the following measures were suggested: pilot and reference plants, WeChat groups, technical literature and education. To acquire new knowledge and promote knowledge transfer, international research projects including pilot plants were mentioned. However, to convince decision-makers of new technologies, industrial-sized reference plants are needed (see the Market Rules and End Users section for more detail). WeChat is a messaging service in China that is widely used in professional contexts. Experts and political actors participate in WeChat groups that are also accessible to foreign companies. Another important measure is the translation of literature such as technical literature and standards. English or Chinese translations of current DWA worksheets concerning operation and plant safety would help disseminate German knowledge on conventional treatment technologies and promote conditions for safe sewage sludge utilisation. Finally, according to an expert from science, education in universities often focuses on wastewater treatment. However, for improved handling of sewage sludge, greater integration is required that includes sewer networks as well as wastewater and sewage sludge treatment and utilisation.

Industrial structure

This dimension focuses on operational issues in plants and suggests different forms of knowledge transfer, operator models and new cooperation arrangements as measures to overcome the barriers. Operational problems in treatment plants are widespread and there can be many reasons for this. In general, there is a shortage of skilled workers and high staff turnover, which not only hamper the operation of plants but also diminish the success of training. One of the experts also reported that training is not successful if it is provided by foreign companies because trainers have no authority if they are not part of a hierarchical structure. Furthermore, another barrier created by strong hierarchical structures is the lack of error communication.

Again, this problem could be addressed by improved knowledge transfer at different levels.

According to the experts, training materials and textbooks could replace training if the knowledge can be provided in English or Chinese. In addition, wastewater treatment plant neighbourhoods are suitable for resolving operational issues, with operators of different wastewater treatment plants getting in touch and discussing their problems and solutions. In Germany, this approach is also supported by the DWA. Moreover, operator models can address operational issues. Public–private partnerships are used for the operation of infrastructure such as waste disposal and wastewater treatment, including sewage sludge disposal in China. In principle, foreign companies also have the opportunity to participate (Schmitt 2020). A common operator model for wastewater treatment plants to support operations is Build–Operate–Transfer (BOT). It should be noted, however, that due to their size and (ownership) structures, the opportunities for German companies and associations to be involved in the operation of plants in China are very limited. A new idea discussed in the interviews is partnerships with companies from the waste management sector in combination with centralised sewage sludge treatment plants. Both the 13th and 14th Five-Year Plans specify centralised sewage sludge treatment plants as a required measure. Centralised sewage sludge treatment could be linked to waste management sites and offers a business model based on a service contract. A prerequisite for the operation of plants is cooperation with a Chinese business or a Chinese subsidiary of a German parent company. Currently there are very few German companies operating plants or interested in the development of this activity as a new business field. A business model of this kind requires either a German or a Chinese partner. In addition to service contracts that include the payment of a disposal fee, another common model in the waste sector is 'Bring or Pay'. Here, a fixed quantity is invoiced, although the actual quantity of waste delivered can fluctuate. On top of the disposal fees, additional income can be generated by high-quality sewage sludge recycling products if these can be marketed successfully. Here, synergies with waste disposal should also be considered, such as co-incineration or electricity production from methane.

Market rules and end users

This dimension includes, in particular, the planning and tendering process, as well as marketing aspects in the field of infrastructure development. For the introduction of new technology, many stakeholders need to be convinced. The Commission for Development and Reform exists at both a national and provincial level. Through this institution, the local government exerts influence on project proposals. Planning, tendering processes and project execution (EPC, Engineering–Procurement–Construction) are led by the Local Design Institutes, which are

state-owned companies. The Local Design Institutes can also participate in tenders from other provinces. Tenders are issued with performance specifications. New treatment technologies cannot be proposed here. In addition, experts reported that there are inaccuracies in the tendering documents, which have negative effects on the implementation and operability of plants. Chinese actors, such as the operator of a wastewater treatment plant, cannot influence the selection of technology used for sewage sludge treatment (Zimmermann *et al.* in preparation).

According to many of the interviewees, marketing at different levels is an important measure. General marketing includes familiar activities such as attendance at trade fairs but also the implementation of reference plants. In order to create a first reference plant in China, it could be installed at a prospective customer's site for a reduced price. There is also project-specific marketing, e.g. establishing contact with important decision-makers, which allows new disposal concepts and technologies to be offered independently of tendering processes. This might also have a positive effect on preconditions for possible implementation.

Cultural significance

This dimension includes aspects concerning Chinese citizens, among whom public resentment and environmental awareness have increased. Environmental pollution is seen as a major problem in China. According to the experts, operators of wastewater treatment plants sometimes fail to deal with technical problems and malfunctioning plants. Alarming reports appear in the news and residents are afraid of negative impacts on their health. In addition, property owners and developers see their land prices at risk of falling if new infrastructure projects are proposed. In some cases, there have been violent protests against infrastructure projects for which there may be different motivations.

> *'In China, it is common to buy a house. Large infrastructure projects often have a negative impact on real estate prices and this is where demonstrations occur. But perhaps this regional protest, tolerated by the state, is also a kind of release valve.' (Interview 11)*

Possible promotional measures are the widespread dissemination of information about the positive effects of modern environmental technology, reinforced by the provision of data, as a step towards establishing trust among citizens.

RESULTS FROM THE EXPERT WORKSHOP

The results from the expert workshop revealed a high level of interest and positive expectations when it comes to doing business in China's water sector. However, there are barriers that are not easy for German companies to overcome. An initial query considering the business potential in the Chinese water sector showed fairly positive expectations: the results for very good, good and moderate were 20, 40 and 40%, respectively. None of the experts expected poor or very poor business development in the medium term.

Table 2 shows a summary of the measures raised and discussed in the interviews, next to the measures mentioned during the expert workshop. The numbers in brackets represent the rating given by the experts. Measures marked with (1) were rated as important by most experts, those with (2) were second most important, and so on. Measures without a number in brackets were not selected as important by any of the experts.

According to the experts' prioritisation, most of the measures selected as important are in the field of institutional and legal preconditions (A), and two out of three received high ratings. The next most important fields were (B) disposal and recycling routes and (E) marketing. Marketing with regard to infrastructure comes down to tendering and planning processes, which again are very close to institutional and legal preconditions. Concerning disposal and recycling routes (B), the suggested measures are aimed at the recycling products themselves, e.g. high-quality fertiliser, soil amendment or energy source. After the experts rated all the measures, four were discussed in more detail (highlighted in bold in Table 2). Three of these were rated as important by the experts; the fourth measure, knowledge transfer, turned out to be a very important point during the discussion and was therefore included.

The three measures added during the workshop can be linked to those that had already been (see Table 2). However, a more detailed discussion revealed important details. The first added measure concerned the improvement of China's law on the circular economy/waste [#8]. The regulations lack a prioritisation of how to handle resources in a circular manner, which means that a simple but clearly phrased order is required such as 'recovery,

Table 2 | Measures and ratings

Field of barrier (dimension)	Measures (interviews)	Additional measures (expert workshop)	Ratings per field
(A) Institutional and legal preconditions (policy and political power)	#1. Influence and support for the development of suitable regulations for sewage sludge in China (2) Cooperation in research projects European-Chinese working groups (e.g. EU-Chamber) Political consulting	#8. Political influence on the development of a Chinese circular economy/waste law (4) #9. **Improvement in processes and practices within specialised authorities (e.g. assessments, decisions, plans and availability of specialist knowledge) (2)**	2/4/2
(B) Disposal and recycling routes (infrastructure)			3/3
Incineration	#2. Quick and preliminary solutions until the utilisation of sewage sludge – increasing co-incineration – volume reduction, stabilisation and safe storage #3. Market products, e.g. as energy source (3)		
Land application	#3. Market products, e.g. as a high-quality fertiliser or soil amendment (3)		
(C) Knowledge	#4. Improved knowledge transfer (2) – German-Chinese research projects and cooperation arrangements – Exchange programmes at universities – Translation of German textbooks and teaching materials – Translation of technical literature such as DWA worksheets – Exchange among experts in WeChat groups		2
(D) Operation and business models (industry structure)	#4. Improved knowledge transfer: – Provide training materials/technical literature in English/Chinese. – Partnerships between WWTP operators **#5. Business or operator models to support the permanent operation of new plants (1)** – Service contracts and additional sale of recycling products – Bring or Pay: centralised sewage sludge treatment or partnership with operators of waste disposal facilities		1
(E) Marketing, planning and tenders (market and end user)	#6. Marketing (5) – General marketing, e.g. full-scale plants for reference purposes (possible with discounting for first application) – Project-specific marketing, e.g. offering tailor-made disposal concepts	**#10. Persuasion of decision-makers in public authorities (1)**	5/1

(*Continued.*)

Table 2 | Continued

Field of barrier (dimension)	Measures (interviews)	Additional measures (expert workshop)	Ratings per field
(F) Environmental awareness and public discontent (cultural significance)	#7. Trust-building activities – Information campaigns on different channels and for different target groups		

Measures marked with (1) were rated as important by most experts, those with (2) were the second most important, and so on; measures in bold were discussed in detail; ratings per field show the importance of the measures among the whole range of barriers.

recycling, destruction'. The second measure added (which was also rated high and discussed in detail) concerned the improvement of processes within specialised authorities [#9]. On a national level, efforts are being made. However, there is a lack of implementation at the middle level (provinces and municipalities). Official procedures in Germany, e.g. administrative systems with specialist know-how and official processes, are regarded as good examples in China, e.g. specialised authority programme, evaluation practices and technical standards on the execution of a specific construction. Members of public authorities in China do not have adequate technical literature. Guidelines, DWA regulations and standards, and different programmes do not exist in either English or Chinese. At this point, the discussion of another measure revealed interesting details about improving knowledge transfer [#4]. One of the experts explained the importance of training in combination with the availability of translated technical literature because of language gaps arising from the different linguistic and cultural backgrounds involved. In addition, it was unclear who would be a suitable actor to take on the task of translating and supplying the latest documents. According to experts from German firms and institutions, there is no equivalent of the DWA in China. It should be noted that it is also clear from the literature and from the expert interviews that sewage sludge standards do not always suit Chinese preconditions with the result of lacking implementation. Thus, there seem to be issues with both the specifications in policy and the implementation of policy. The third measure added during the workshop and given a high priority was persuading the decision-makers in public authorities [#10]. Due to a lack of time, this measure was only discussed very briefly. Furthermore, it can be linked to two measures that had already been introduced on the basis of the interviews. Firstly, decision-makers can be persuaded and new technologies disseminated with the support of German-Chinese research projects and cooperation [#1]. If well connected, Chinese experts can be successful at presenting promising technologies and the associated requirements to decision-makers. Secondly, persuasion is also at the core of project-specific marketing, especially when offering tailor-made disposal concepts and technologies independently of tendering processes [#6]. For all these measures, good contacts with decision-makers are required, something that was reinforced during the discussion.

Business models [#5] were rated as very important and discussed in detail with the experts. In the context of introducing the interview results and the measures that had been developed beforehand, new business models were shown that involve new kinds of cooperation, including partnerships with companies from the waste sector. The idea of running centralised plants for sewage sludge treatment as BOT or 'bring or pay' was also mentioned.

However, the experts did not pick up on either option during the discussion. This might have been due to the structure of the German companies, which is unsuitable for operating plants abroad. Moreover, only one of the companies represented during the workshop is considering expanding its business activities to China. The discussion of this measure mainly revolved around the preconditions for market entry in China and once again revealed the multiple barriers seen by the experts from German companies.

Most of the measures mentioned here can be linked to the measures mentioned by the experts from Chinese firms and institutions (Zimmermann *et al.* in preparation). Representatives from German companies and institutions did not mention the improvement of the wastewater infrastructure as a measure, while the Chinese experts did not mention political consulting, preliminary solutions, marketing measures or trust-building measures. In most cases, these gaps are in line with the different perspectives held by the two groups of experts.

Froese *et al.* (2019) give an extensive overview of challenges for foreign companies linked to the regulatory environment, cultural aspects, human resource management and innovation management in China. Moreover, managerial implications are presented, including measures such as investing in political connections and

influencing policy-making, hiring and investing in local human resources, offering development and career opportunities, recruiting returning Chinese citizens to bridge cultural and linguistic divides, and working with local organisations that have the appropriate capabilities (ibid).

CONCLUSIONS

The conceptual framework applied in this study was helpful for drafting the interview outline for the semi-structured interviews. During the qualitative data analysis, the dimensions of the framework also covered all the aspects raised by the experts. The results show that some dimensions had to be focused on and clustered according to specific interrelations, such as infrastructure and policy or market rules and planning. Nonetheless, working with the framework showed that it is suitable as a basis and starting point for obtaining a holistic picture of socio-technical innovation and analysing barriers and measures.

The combination of expert interviews, the literature review and the expert workshop was useful for highlighting the barriers to and measures for sewage sludge utilisation in China. Despite all the experts participating in the workshop being interviewed beforehand, new and very interesting details emerged during the discussion in which they participated. One of the researchers' intentions was to offer space for jointly developing a recommendation for action based on the discussion of the measures during the expert workshop, but this did not happen.

The results show the ambivalent attitudes of German companies in the field of resource-efficient sewage sludge treatment for improved utilisation in China. The workshop clarified that there are great opportunities in this sector, but the barriers in place at the moment are very hard for foreign companies to overcome. The prioritisation of the measures shows that the experts see great interdependencies between factors that they cannot influence or, if so, only with difficulty and great commitment. Business models based on the operation of new treatment technologies for sewage sludge utilisation, such as AD, THP and HTC, do not seem feasible for many German companies in this sector. It became clear that one of the most important prerequisites for overcoming barriers is strong ties with Chinese partners and a spirit of international cooperation.

It should be noted that this study had its limitations and further research is required to improve understanding of the feasibility of measures and implementation strategies based on regional specifics on a smaller scale. Further research should also focus on synergies between waste and sewage sludge treatment, such as new co-incineration potential due to a change in the waste fractions of comingled waste or new business models linking both sectors. The science–policy interface is an important field of study with regard to sewage sludge in China, as well as the requirement for harmonisation of policies and laws.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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