Technical and economical viability of a graywater recycling system employing an integrated preliminary settlement & filtration process

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ABSTRACT

The collection and reuse of graywater has become an important strategy for achieving the goal of sustainable development. In this work, an integrated preliminary settlement and filtration process was developed for treating shower water which was obtained from a college bathroom toilet. The system’s pollutant removal efficiency was examined for three different filter media: manganese sand, quartz sand and ceramsite. The results showed that for ceramsite, the average removal of turbidity, CODcr, NH3-N, and anionic surfactant was 93.3%, 68.6%, 78.9, and 83.5% respectively. For manganese sand, the values were 84.6%, 61.5%, 57.8 and 59%, while for quartz, they were 88.9%, 47.9%, 39.5% and 51.9%. A cost–benefit analysis revealed that the payback period of graywater recycling systems ranges from 3.16–5.30 years and benefit–cost ratios are in the range of 1.23–1.67, depending on tank size. The proposed system provides a new strategy for enhancing water-use efficiency in buildings in a more decentralized way.

Key words: cost benefits, graywater reuse, payback period, removal efficiency

HIGHLIGHTS

• An integrated preliminary settlement and filtration process was developed for shower water treatment.
• Ceramsite filtering medium was found to be effective to filter graywater to meet the non-potable standard.
• The graywater recycling system is economically viable when the potable water price is higher than 2.52 CNY/m³.

INTRODUCTION

The world is facing a serious challenge to satisfy the water demands for human activities with the increasing population, continued urbanization, and over-exploitation of water bodies (Kim et al. 2007; Mandal et al. 2011). To overcome these challenges, it is necessary to adopt a sustainable approach towards water management (Bagatin et al. 2014). Reuse of waste water or graywater to substitute non-potable water consumption in buildings is not a novel concept but a powerful tool for sustainable water management (Lyu et al. 2016; Zhang et al. 2019). Although graywater recycling (GWR) has been practiced in many countries, nevertheless, there are multiple barriers against further implementation of this system in buildings. Bathroom graywater represents one of the alternative water sources (Tsoumachidou et al. 2017). However, bathroom graywater contains chemical contaminants such as soaps and detergents (Mohamed 2011). Therefore, for reducing the impacts of pollution on the human health, the development of effective and economic lightly polluted graywater treatment methods is thus required urgently (Antonopoulou et al. 2013).

Investigations for the treatment of bathroom graywater have been previously reported from a wide range of filtration processes such as sand bed, gravel, charcoal bed, course size bricks bedded, coconut shell cover, steel slag, clamshell, and wooden saw dust bed in many literatures (Mohamed 2011; Antonopoulou et al. 2013; Wu et al. 2015; Fountoulakis et al. 2016; Son et al. 2016; Zhang et al. 2016). Among these media, sand filtration is one of the most commonly used wastewater treatment process and has many advantageous due to simple removal mechanisms, lower maintenance cost and small footprint (Esen et al. 1995). Despite such advantages, however, sand filtration systems often fail to meet reclaimed standards that are more stringent in recent days. As such, improvement of sand filtration is necessary which can provide significant removal of ammonia nitrogen and organic compounds while maintaining the major advantages of the sand filter systems (i.e. simplicity, low cost...
and low maintenance) (Hasan et al. 2019). Porous media with strong adsorption capacity such as granular activated carbon (GAC) and anthracite have been widely used in surface water treatment and were able to treat raw water to a very high quality (Kim et al. 2008). However, the major problem of these processes is that it may suffer from severe fouling when these porous media were used for wastewater or graywater treatment thus requires frequent physical and chemical cleanings, leading to high capital cost and difficult maintenance. These disadvantages make it necessary to explore new technologies and schemes for wastewater and graywater reclamation.

As mentioned above, the current sand filter does not meet the increasingly stringent water reuse standard requirements, as the porous filters are prone to becoming blocked by reclaimed water which often contains a significant amount of particulate impurities. Adding pre-sedimentation before the filtering process is assumed to overcome these defects as a significant amount of impurities which may cause pore blockage in the filter medium are retained in the settlement chamber. This means that the improved process not only retains the advantages of simplicity and lower maintenance costs, but is also highly efficient in removing contaminants. For this study, a novel integrated preliminary settlement and filtration (IPSF) process is established for the treatment of lightly polluted graywater in a decentralized way. This process produces a combination of the settlement process and filtration phase in one compact unit. As a consequence, the selection of filter media in this process is a new concern.

The selection of filter material primarily considers the following factors: namely uniformity coefficient (UC), effective size (ES), surface roughness, and density, and seldom it is also dictated by specific treatment goals like removal of organics or extending filter running time (Sharma et al. 2018). Among one of the most frequently utilized filtering media in surface water treatment, the quartz sand has benefits such as high mechanical strength, strong pollution interception ability, and long service life, etc. Manganese sand, another inexpensive and easy-to-obtain filter material is increasingly received as a method for the slightly polluted wastewater treatment because of its strong catalytic oxidation characteristics (Liu et al. 2010). As an emerging filter material, light ceramicite has a relative density of 1.1 g/cm³, and a specific surface area of 13,600 cm²/g, making it the same strong adsorption capacity as GAC (Sharma et al. 2018). Previous studies have reported substantial removal (over 93%) of iron, manganese, and phosphorus (Hasan et al. 2015) from groundwater because of the effective floc separation performance of the ceramicite filter system. This material was also used in the MBR process to treat wastewater with satisfactory removal performance of different pollutants for instance 97–100% of BOD, 96–100% of COD, 98–100% of TOC, more than 98% of nitrogen and more than 96% of phosphorus (Hasan & Nakajima 2014). These results signify that the light ceramic filter might also offer a simple approach to improve the effluent quality of graywater which has not been reported to date.

Besides the security reasons of graywater reuse, another obstacle against its further implementation maybe because of the lack of adequate information on the benefits of a graywater recycling system (Hwang et al. 2006; Philp et al. 2008; Wu et al. 2012). First of all, within China, there are very limited examples of thorough monitoring of the graywater reuse in buildings. Secondly, so far, the research on financial feasibility of graywater recycling system has not been prominent in the literature, and also the findings of these studies are usually contradictory (Philp et al. 2008). The majority of the house owners do not promptly see the benefit of the GWR system over longer-term (Rahman et al. 2012). Consequently, it is extremely vital to observe the economic feasibility of a graywater reusing system.

The proposed IPSF system was installed to supply water for toilet flushing purposes at a college bathroom of Zhongkai University of Agriculture and Engineering in the north of Guangzhou, China. This paper explores the highly relevant technical and economic concerns of the GWR system. For the purpose of comparative study, quartz sand, manganese sand, and ceramicite was utilized in the proposed IPSF unit as a filtering medium for graywater treatment, respectively. The technical performance of the IPSF process has been discussed from the perspective of pollutants removal efficiency, whereas the economic feasibility of this proposed GWR system was assessed in terms of payback period and benefit–cost ratio.

**MATERIALS AND METHODS**

This section presents the description of the IPSF unit, the detection and analysis methods used in this study.

**System description**

The graywater for this experiment was obtained from a bathroom of a student apartment in ZhongKai Agricultural Engineering College in Guangzhou, China. As indicated in Figure 1, the facilities were ‘wall-mounted’. The shower water and hand washing graywater from the ground of the upstairs bathroom are captured (Figure 1). In the target building, every six bathrooms share a GWR system, and each bathroom serving six students.
An integrated preliminary settlement & filtration tank measures 1,200 mm × 300 mm × 1,000 mm in size was designed and constructed. A baffle wall divides the tank into two compartments—a settlement chamber (0.105 cubic meters m³, or 105 liters) with a conical bottom for sediments emission, and a filtering chamber (measuring 840 mm × 300 mm × 1,000 mm, as show in Figure 2). The filtering chamber encompasses a 300 mm pebbles layer (act as a bearing layer) in the bottom and a 400 mm filtering layer in the upper. Three different filter materials: manganese sand (provided by Guangzhou Suiyun Water Supply Co., Ltd, Guangzhou, China), quartz sand (Supplied by Guangdong Weirong Environmental Protection Technology Co., Ltd, Guangzhou, China) and light ceramsite (purchased from Zhongqing Environmental Technology Co., Ltd, Shenzhen, China) were used in the IPSF unit for efficiency test of graywater treatment, respectively. The morphologies of the three filter media are shown in Figure 3. The physical–chemical properties of the three filter media are shown in Table 1.

Process operation

Figure 2 illustrates how the system behaves under various operating conditions. The harvested graywater first enters the settlement chamber, where the silt gets deposited. To prevent trapped materials such as hair, soap,
toilet paper, and diapers from entering into the filtering chamber, the inlet of the chamber is covered with a net (with pore size of 1.5 mm × 1.5 mm). The silt-free water then pass through the filtering chamber (a double-layer filter bed) in an up-flow direction at a slow flow rate of 2.0 mm/s, which further filters the graywater to ensure the quality of which is being recharged. The treated water is diverted to the storage tank of the toilet for flushing use (Figure 2). Any excess of water, with respect to the storage capacity of the tank, is drained into the sewer system through a tank overflow pipe. The average hydraulic retention time of the system was approximately 1.5 hours.

The whole system was continually run for 1 month from June 27 to July 28, 2019. During the filtration operation, back-washing was applied to remove excess particles that can cause filter clogging. This operation require to close the inlet valve, to open the tap water valve to reverse the flow in the system and open the drain valve at bottom of the settlement chamber to discharge the flushing water. After the complete drainage of the system, the backwash outlet closes, and the system is reset to start the filtration again.

Analytical methods
This study evaluated the performance of the proposed technology. Laboratory experiment was conducted to evaluate the technical feasibility of IPSF process in the treatment of graywater, while payback period and benefit cost analysis was performed to assess the economical viability of the novel graywater recycling system in the target building.

Water quality analysis
During the experiments, water samples were taken from the inlet and outlet of the IPSF unit for the measurement of water qualities, and then compared against the Miscellaneous Domestic Water Standard (GB/T 18920-2002), one of the Chinese Recycling Water Guidelines (CRWG) published by General Administration of Quality supervision, Inspection and Quarantine of the People’s Republic of China. In this study, examined water quality indicators consisted of pH, Turbidity, total dissolved solids (TDS), SS, Color, Odour, BOD$_5$, CODcr, NH$_3$-N, Hardness, Chloride, Anionic surfactant (LAS), Iron, Manganese and Total Coliforms, all of these items are prescribed by the CRWG. The pH was determined by a pHS-3C pH meter (Rex Electric Chemical, China). The turbidity was measured using a portable turbidity meter 2100P (HACH, USA). The TDS was measured by a SX650 Pen type TDS instrument (Shanghai SanXin Company). Suspend Solid (SS). Iron and Manganese, hardness, Chemical oxygen demand (CODcr), Ammonia nitrogen (NH$_3$-N), BOD$_5$, LAS and other parameters were measured according
to the water and graywater monitoring and analysis method (State Environmental Protection Administration 2002). All tests were duplicated to ensure reproducibility of the results. The recommended test items and their limits of the CRWG, as well as the quality of raw graywater are presented in Table 2. As shown in Table 2, there are several water quality items in the raw graywater that are within the standard limits, therefore, only four items (exceeding the standard limit) were tested for the effluent quality analysis, they are turbidity, CODcr, NH$_3$N and anionic surfactant (LAS).

**Economic analysis**

In this study, the economical viability of the proposed graywater recycling system was evaluated using two economic indicators, which were payback period (PBP) and benefit–cost ratio (BCR) (Morales-Pinzon et al. 2014).

The PBP, is measured as the ratio between total capital costs and the difference between annual revenue and annual expenditures, taking into account the discount rate (Farreny et al. 2011). Whereas the benefit–cost ratio is estimated as the ratio of the sum of all the discounted benefits and discounted costs. All projects with BCR > 1.00 are considered viable investments (Severis et al. 2019). These indicators are calculated use the following formulas:

\[
PBP = \frac{\sum_{t=0}^{s} I_t + M_t}{S_t P_t - (I_t + M_t)} \left(1 + \frac{r}{1} \right)^t
\]

\[
BCR = \frac{\sum_{t=0}^{s} S_t P_t}{\sum_{t=0}^{s} I_t + M_t} \left(1 + \frac{r}{1} \right)^t
\]

where $S_t$ is the volume of water saved over a period of time t (m$^3$), $P_t$ is the price of potable water over a period of time t (CNY/m$^3$), $I_t$ is the investment required for a period of time t (CNY), $M_t$ is the operating and maintenance costs over a period of time t (CNY), $s$ is the life span of system (year), $t$ is the system operation period (year), and $r$ is the interest rate (%).

Life span of the system is estimated at 20 years and a discount rate of 6% is consider according to the economic evaluation methods and parameters of municipal public facilities construction projects.

**RESULTS AND ANALYSIS**

The following subsections presented the removal efficiency of the IPSF unit (Pollutants removal of the IPSF unit), detail the results of drinkable water savings (water saving potential) and benefit–cost analysis (Cost and Benefit analysis) of a graywater recycling system that employed a IPSF unit.

**Table 2 | The initial pollutants of captured graywater**

| Parameters   | Range   | CRWG limit | Parameters   | Range   | CRWG limit |
|--------------|---------|------------|--------------|---------|------------|
| pH           | 6.8–7.4 | 6.5–9.0    | BOD$_5$ (mg/L) | 1.3–8.5 | 10         |
| Color        | 4–19    | 30         | Hardness (mg/L) | ≤30     | 450        |
| Odour        | No odour | No odour   | Chloride (mg/L) | 3.3–14.5 | 300        |
| Turbidity (NTU) | 14.5–34.03 | 5        | Iron (mg/L) | ≤0.1    | 0.4        |
| SS (mg/L)    | 2.6–6.7 | 10         | Manganese (mg/L) | Not detected | 0.1      |
| TDS (mg/L)   | 267–343 | 1,000      | LAS (mg/L) | 1.92–5.01 | 1.0        |
| CODcr (mg/L) | 99–126  | 50         | Total coliform | Not detected | 3 cells/L |
| NH$_3$N (mg/L) | 26.9–37.9 | 10     |               |         |            |

*Note: CRWG, Chinese Recycling Water Guidelines.*
Pollutants removal of the IPSF unit
The main pollutants in the graywater are the secretion from human body, grease and dandruff, hair and detergent, and other compounds. The concentration of bacteria, BOD₅ and suspended solids in this graywater is relatively low, while the contents of detergent, NH₃-N are higher than that in other domestic sewage. As illustrated in Table 2, the harvested graywater is of relative high quality with most indicators complying with the standards for Miscellaneous Domestic Water (GB/T18920-2002), except for turbidity, surfactant (LAS), chemical oxygen demand (CODcr) and ammonia nitrogen (NH₃-N) (Table 2). Therefore, in this study, the efficiency of the IPSF process has been discussed in terms of turbidity, CODcr, NH₃-N, and LAS. Figures 4–7 compare the examined water quality parameters of effluents from the IPSF unit that is employing manganese sand, quartz sand and ceramsite as filtering media.

During this experiment, the turbidity in graywater was 24.3 ± 9.8 NTU on average (Table 2). It can be seen from Figure 4, for the turbidity, an average removal of 84.6% was achieved by the manganese sand filter, with a moderate level of 3.75 ± 1.2 NTU remaining in the graywater. The quartz sand filter removed turbidity on an average of 88.9%, so that a level range of 2.70 ± 0.84 NTU still remained in the filtrates. As for the ceramsite filter, the IPSF unit removed turbidity on an average of 93.3%, and resulted in a turbidity of no more than 2 NTU remaining in the filtrates. The turbidity in all effluents from three filter medium well satisfied the CRWG, which has a recommended limit for turbidity of 5 NTU, these results demonstrated that all of three filter media perform well in the removal turbidity from graywater.

The CODcr detected by potassium dichromate was used to represent the organic pollution degree of graywater. In current study, harvested graywater was of a good quality, which contained an average CODcr concentration of 113.6 mg/L within a range of 99–126 mg/L (Table 2). It can be seen from Figure 5, that the manganese sand,
quartz sand and ceramsite filter system reduced the CODcr by an average of 61.5%, 47.9% and 68.6%, to levels of 43.7 ± 13.6, 59.2 ± 11.8 and 35.7 ± 11.9 mg/L, respectively. However, after the IPSF treatment, the CODcr concentration in effluent from manganese sand and quartz sand filters still exceeded the CRWG limit of 50 mg/L. It was suggested that the manganese sand and quartz sand filter rejections of organic matter (indicated as CODcr) were undesirable. As shown in Figure 5, the removal rate of CODcr by the ceramsite filter was 7.1% and 20.7% higher than those in the manganese sand and quartz sand filters, with its effluent within the recommended limit of the urban miscellaneous water standard.

As shown in Table 2, IPSF influent NH3-N fluctuated between 26.9 and 37.9 mg/L during the experimental period. As observed in Figure 6, the manganese sand filter and quartz sand filter contributed on average 57.8% and 39.5% removal of NH3-N, with 14.03 ± 4.07 mg/L and 20.11 ± 4.86 mg/L ammonia nitrogen remained in the graywater, respectively. However, the effluent NH3-N concentrations were still beyond the CRWG limit of 10 mg/L, which makes these treated waters unsuitable for domestic use. As illustrated in Figure 6, the IPSF process using the ceramsite filter reduced the NH3-N by an average of 78.9% to levels of less than 9.4 mg/L, below the limit of the Chinese Urban Miscellaneous Water Consumption standard. As was obvious, the ceramsite filtering medium is preferable for rejection of small molecular pollutants (indicates as NH3-N) than manganese sand and quartz sand filters. This may be related to the strong adsorption capacity of the ceramsite filter material.

The concentration of LAS in the feed graywater ranged from 1.92 to 5.01 mg/L (see Table 2). As can be seen from Figure 7, the effluent LAS concentrations were found at 1.37 ± 0.89 mg/L, 1.61 ± 0.00 mg/L and 0.55 ± 0.31 mg/L.
from the manganese sand filter, quartz sand filter and ceramsite filter during the experimental period, respectively. This suggests that ceramsite is the most effective filtering material among the three tested media to remove surfactants from graywater, the surfactant concentrations in effluents from IPSF unit completely met the non-potable water quality standard.

According to experimental results, it is apparent that although the manganese sand and quartz sand filters had contributed significant proportions of pollutant removal from harvested graywater, there was still a great amount of COD\textsubscript{cr}, surfactant, and NH\textsubscript{3}\textsubscript{-N} that remained in the effluents, which makes the treated water unsuitable for domestic uses such as laundry, hand washing, and cleaning due as the quality could not satisfy the urban recycling water standard. Current experimental results demonstrated that the ceramsite filter significantly outperformed manganese sand and quartz sand filters in contaminants rejection, especially in low-molecular substances (indicated by COD\textsubscript{cr} and NH\textsubscript{3}\textsubscript{-N}) removal, and was the unique among the three examined filtering materials to treat graywater with all examined indicators and completely satisfy the standard for Chinese Urban Miscellaneous Water Consumption.

**Water saving potential**

The proposed IPSF device was intended to be installed at a college apartment building, where the water consumption pattern as well as the amount of daily graywater release were monitored. The non-potable water demand (only toilet flushing is considered) and the hourly graywater consumption are summarized in Table 3.

Since the discharge of graywater was not always synchronized with the non-potable water demand, for instance, the discharge of graywater primarily occurred from 18:00 to 24:00, which accounted for 80% of the total daily consumption of graywater, whereas the consumption of non-potable water was evenly distributed throughout the day, thus a storage tank needs to balance the difference between the discharge of graywater and the demand for non-potable water. The capacity of the storage tank has a significant impact on the water saving potential of the GWR system. In general, the volume of graywater that can be collected is limited by the capacity of the storage tank, that is the larger the tank size, the more graywater can be collected. Nevertheless, it should be observed here that, the oversize design will increase the total investment of the system, resulting in a lower benefit–cost ratio. In this study, in order to determine the optimal storage tank, a water balance simulation model tailored to the target apartment on an hourly time scale was constructed that considered a series of storage tanks ranging from 0.12 to 3 cubic meters.

**Figure 8** shows the effects of storage tank size on the volume of water saving for the graywater reuse system. It can be seen from the figure that there are two obvious stages of the water saving for the graywater reuse system. In the first stage, the amount of water saving increases significantly with increasing storage tank sizes in the range 0.12 m\textsuperscript{3} to 1.2 m\textsuperscript{3}. For this stage, it is apparent that increasing the tank capacity provides an opportunity to store more graywater. However, the water saving reaches a plateau at 3,928.2 liter (2nd stage) as the proposed tank size

| Time (hour) | Graywater discharged (L) | Water demand (L) | Regulating volume (L) | Time (hour) | Graywater discharged (L) | Water demand (L) | Regulating volume (L) |
|------------|--------------------------|------------------|-----------------------|------------|--------------------------|------------------|-----------------------|
| 0–1        | 184.8                    | 54.6             | 130.2                 | 12–13      | 145.5                    | 243.7            | –98.2                 |
| 1–2        | 59.7                     | 13.4             | 46.3                  | 13–14      | 154.8                    | 230.8            | –76                   |
| 2–3        | 14.4                     | 3.5              | 10.9                  | 14–15      | 171.2                    | 262.6            | –91.4                 |
| 3–4        | 8.7                      | 5.8              | 2.9                   | 15–16      | 113.4                    | 182.4            | –69                   |
| 4–5        | 5.2                      | 7.9              | –2.7                  | 16–17      | 162.2                    | 208.6            | –46.4                 |
| 5–6        | 12.5                     | 76.4             | –63.9                 | 17–18      | 237.4                    | 175.7            | 61.7                  |
| 6–7        | 27                       | 132.3            | –105.3                | 18–19      | 233.7                    | 166.5            | 67.2                  |
| 7–8        | 15.2                     | 256.7            | –241.5                | 19–20      | 280.9                    | 220.1            | 60.8                  |
| 8–9        | 42                       | 231.4            | –189.4                | 20–21      | 327.5                    | 121.9            | 205.6                 |
| 9–10       | 57.7                     | 225.8            | –168.1                | 21–22      | 334.8                    | 144.7            | 390.1                 |
| 10–11      | 127.1                    | 303.3            | –176.2                | 22–23      | 544.4                    | 257.6            | 286.8                 |
| 11–12      | 132.6                    | 214.5            | –81.9                 | 23–0       | 335.5                    | 241.4            | 94.1                  |
is able to collect the total graywater discharged from upstairs bathrooms (see Figure 8). Therefore, it was useless to increase the tank size to more than 1.2 cubic meter. It can be concluded from Figure 8 that, for the given non-potable demand pattern, a 1.2 m³ tank is sufficient to achieve maximum water saving, an unnecessarily large storage tank would be a misuse of investment and space.

**Cost and benefit analysis**

The costs analysis considers the initial investment and operating costs of the GWR system. The initial investment include the facilities expenses and installation cost. According to the proposed graywater collection and treatment process, apparatus and materials mainly consist of an IPSF unit, filter material, valves and pipelines, elbow and tee joint, etc. Cost information of the GWR system components was obtained from a market survey. The components of the graywater reuse systems were inventoried and their detailed prices were supplied by retailers in Guangzhou, China. The aggregation of the components prices and installation costs compounded the initial investment. Table 4 provides a summary of the initial investment (excluding rainwater tank) of a waste water recycle (WWR) system. The estimated total facilities expenses are 5,786.72 CNY (Table 4). The installation cost is estimated at 10% of the total facilities expenses, which is equivalent to 578.6 CNY. The storage tank is the

**Table 4** | Initial investments of target graywater recycling system

| No. | Item                                | Unit | Amount | Unit price(CNY) | Total price(CNY) |
|-----|-------------------------------------|------|--------|-----------------|------------------|
| 1   | IPSF device                         | 1    | 3,800  | 3,800           |                  |
| 2   | Hair filter                         | 1    | 140    | 140             |                  |
| 3   | Water level control valves          | 1    | 480    | 480             |                  |
| 4   | Flow meter (DN 50)                  | 2    | 110    | 220             |                  |
| 5   | Cobblestone                         | kg   | 55     | 2.6             | 143              |
| 6   | Filter materials                    | kg   | 33.5   | 11.52           | 385.92           |
| 7   | Pipelines (DN50,1.6 MPa)            | Meter | 24.5 | 15.42           | 377.8            |
| 8   | 90 degree elbow                     | 8    | 1.0    | 8               |                  |
| 9   | Tee joint                           | 4    | 19     | 76              |                  |
| 10  | Gate valve                          | 6    | 26     | 156             |                  |
| 11  | Installation costs (including labor cost) | 10% of total facilities expenses | |

| Total cost | 6,365.39 |

*Note: Average currency data from 07/2019 to 07/2019, 1 CNY was equal to 0.1427 USD; Filter material is estimated by the expenses of light shale ceramsite.*

![Figure 8](image) **Figure 8** | Effects of tank sizes on the water saving of the GWR system.
most expensive individual components for a WWR system. The expense of water tank ranges from 130 to 1,228 CNY depending on sizes (as listed in Table 5). Therefore, the total investment may varies between 6,540.39 and 8,615.39 CNY.

For the estimation of operating costs, the periodic replacements of filter materials have been taken into account, however, the labor costs and losses during maintenance period were ignored. According to the experimental results, the filtering materials are required to be replaced every 2 months on average, equivalent to 2,315.5 CNY per year. In addition to normal operation, power and tap water are required for sludge discharge and back-washing of settlement chamber as well as the filter bed. In consideration of the water and electricity used are irregular, the costs of which are estimated at 10% of the total initial investment according to empirical data drawn from existing WWR systems, that equal 231.6 CNY per year. In addition, depreciation of equipment is considered in the cost analysis. In this study, the annual depreciation cost is estimated at 4% of the total capital costs, which is 281.4 CNY per year. Therefore, the total operating cost of the graywater recycling system is 2,815.1 CNY per year.

The benefits of this system are obtained from the income of water saving. With the original water saving data as referred above, economic analysis converts the water savings into monetary benefits, the annual revenue is calculated by the product of potable water savings and water tariff. The water tariff in 2019 is 3.88 CNY per cubic meter according to the price released by Guangzhou Water Supply Company. According to Figure 8, a 1.2 m³ storage tank is confirmed to be optimal for harvesting all abandoned graywater, and a daily average of 3.93 m³ drinkable water was estimated to be replaced by regenerated shower water, therefore the annual revenue can be calculated by 3.88 × 3.93 × 365 that is equal to 5,563 CNY.

One way to evaluate the economical viability of installing a graywater recycling system is to estimate the time period required to recover the project investment. In order to be competitive, a return on investment is expected within a reasonable period of time, the so-called PBP (Silva et al. 2015). In this study, the PBP is measured as the ratio between total capital cost and the difference between annual revenue and annual expenditure (as formula 1). The benefit–cost ratio is another basic standard which evaluates the economic benefit of investment, and the judgement whether an investment plan is feasible or not, which has the characteristics of simple calculation and visible. In this study, the benefit–cost ratio is determined by comparing the present value of accumulated expenditures with the accumulated income within lifespan of the recycling system (as Equation 2). For a given graywater discharge pattern and water consumption profile, both of the PBP and benefit–cost ratio of the system may greatly depend on the volume of water tank employed in the target system. The detailed financial predictions of the proposed WWR system are presented in Figure 9.

As illustrated in Figure 9, the benefit–cost ratio of this project increases with tank size increasing from 0.12 m³ to 1.2 m³ and decreases thereafter, while the trend of PBP is just the opposite. Benefit–cost ratio of the WWR system ranges from 1.23 to 1.67 and the PBP of this project is in the range 5.30–3.16 years depending on tank size. The benefit–cost ratios are above the desired value of 1.00 and the PBPs are far less than the lifespan of the project for all the 13 different tank scenarios, respectively, suggesting that the project is financially viable.

As shown in Figure 9, for the target project, the highest benefit–cost ratio is 1.67 for a 1.2 m³ tank scheme, while the lowest is 1.23 for a 0.12 m³ tank scenario, which agreed well with the benefit–cost ratio results, the shortest payback period of investment (3.16 years) is achieved for a 1.2 m³ tank, and the longest PBP (5.30 years) is calculated for a 0.12 m³ tank. These results highlight the fact that in the target WWR system, a 1.2 m³ storage tank is the optimal scheme to achieve the maximum economic benefits. When within the range from 0.12 m³ to 1.2 m³, a relatively larger tank is preferable to a small one to achieve better financial outcome for the home owners, although employing a larger tank may increase the initial cost, after that, the user will paying more for less increase in benefit when changing from a 1.2 to 3 m³ tank compared to choosing a 1.2 m³ tank.

Table 5 | Price of storage tank with various size

| Size (m³) | 0.12 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 1.0 | 1.2 | 1.5 | 2.0 | 3.0 |
|----------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Price (CNY) | 175 | 300 | 475 | 478 | 573 | 620 | 718 | 790 | 845 | 1,108 | 1,298 | 1,900 | 2,250 |

Note: The price information in the table comes from market survey.
Water price is another main factor that governs the financial performance of graywater recycling systems (Morales-Pinzon et al. 2015). It should be noted that the yearly monetary savings is calculated through multiplying the reduction of potable water consumption by unit water price. When the water price increases, the yearly monetary savings will be increased and the PBP will be shortened (Mohammad et al. 2018). The local water price depends on several factors, such as water availability, type of treatment process adopted, installation and maintenance of the distribution system, and household consumption level (Severis et al. 2019). To calculate benefit–cost ratio and PBPs, future water price needs to be predicted. In this regard, due to water contamination and climate changes, the future drinking water price is expected to rise (Ding et al. 2017). In practice, during 2004–2018, Beijing and Guangzhou had experienced 72.4 and 122% increases in household water prices, respectively, which suggests an annual increase of 5–9% in the next decade.

Figure 10 shows the effect of variations in drinking water prices on the benefit–cost ratio and PBP indicators. It can be observed that there is a significant linear relationship between the benefit–cost ratio and the local water price, an increase in the drinking water price from 2.0 CNY/m³ to 8 CNY/m³ (which represents a four-fold increase) would give a 4.36-fold growth in benefit–cost ratio of the graywater reuse system. It should be noted
that the water price considered in this study is 3.88 CNY per cubic meter (2019 Guangzhou water price), an increase in the current water price to 5.5 CNY/m³ (which represents a 41.8% increase within next 5 years) would give a 44.9% increase in benefit–cost ratio and give a 47% decrease in PBPs, suggesting that the graywater reuse system will produce higher revenue with increasing water price in the future due to continued depletion of available water sources. As illustrated in Figure 10, it can be calculated that the PBP will rise to more than 20 years in regions where the water price is less than 2.2 CNY/m³, implying that the WWR system is not economically viable in these regions as the expected lifespan of this system is only 20 years.

**DISCUSSION**

In the current experiment, the performances of the IPSF unit in lightly polluted graywater treatment were examined for three different filter media: manganese sand, quartz sand, and light ceramsite, respectively. The outcomes indicated that the recorded average removal rates relating to turbidity, CODcr, NH₃-N, and LAS were equal to 93.3, 68.6, 78.9, and 83.5% for the ceramsite filter; these were 84.6, 61.5, 57.8, and 59% for manganese sand filter medium; and were 88.9, 47.9, 39.5, and 51.9% for quartz sand filter, respectively. The effluent qualities from the ceramsite filter fully meet the Miscellaneous Domestic Water Quality (MDWQ) standard. Whereas in the manganese sand filter and quartz sand filter, some individual parameters like the NH₃-N and LAS did not meet the (MDWQ) standard. As clearly shown, the ceramsite filter could effectively improve the removal efficiency of organic pollutants. While compared to membrane filtration process, the IPSF unit using ceramsite will not cause membrane blockage, thus reducing the cost of replacing membranes regularly. As a chemical-free process, the IPSF is attractive since it offers a simple approach to support pollutants removal from graywater.

Many previous publications have also documented that the ceramsite filter materials performed well in graywater treatment, e.g., Mohamed et al. (2018) recorded the removal efficiency of COD as between 45 and 70% after ceramsite filter treatment. Whereas in another study, Mohamed et al. (2018) reported that 0.25 mm ceramsite particles reduced COD, TSS, and turbidity 38.8–39.8%, 58.47–59.59%, and 88.31–89.02%, respectively. Similarly, Son et al. (2016) reported that almost 80% of the nitrogenous substances were removed when using ceramic materials as filter media in the post treatment of municipal graywater. In our experiment, the removal efficiency of CODcr was somewhat higher than that of literature reported. This was probably attributed to the IPSF unit which encompasses a settlement process prior to filtration. The sedimentation process prevents substantial amounts of particulate impurities from entering the filter chamber, thus reducing the blockage of the filter medium without back-washing.

The ceramsite filter presented a higher removal efficiency than manganese sand and quartz sand filtering media mainly due to its superior adsorption capacity. Similar to the GAC, the ceramsite medium (139,278 m²/m³) has a surface area of ten-fold more than sand (12,164 m²/m³) and manganese sand (15,404 m²/m³) (French 2012). Such characteristics contribute to its two-stage filtration mechanisms, namely adsorption and interception. The absorption function, which occurs mainly in the early stage of filtration, also helps to removal contaminants from graywater (Saiyood et al. 2012). Another potential mechanism for this behaviour is likely to be attributed to the surface catalysis which involves adsorption of the organic compounds onto the ceramsite filter materials (α-Al₂O₃ in this case) (Zhang et al. 2019). The major functional groups of the ceramsite filter media were C = C, C = O, C-O-H and OH, which can be responsible for significant portions of the reductions of pollutants in the graywater (Mohamed et al. 2018). The chemical composition analysis of the ceramsite medium revealed that the Al₂O₃ was the predominant compound in the medium (43.6%). While in another study, Huang et al. (2016) have observed that Al₂O₃ can effectively catalyze most organic matters (represented by COD). In addition, the functional groups on the surface of ceramsite filter medium such as the presence of the carbonyl groups (C = O) have the ability to be exposed to the interface of the (Al₂O₃, SiO₂) filter media resulting in the attraction of the organic pollutants from graywater to the surface of ceramsite filter medium due to the binding efficiency between the graywater molecules and the negatively charged binding sites (Mohamed et al. 2018).

As presented previously, the benefit–cost ratio and PBP of the graywater reuse system showed a significant two-stage pattern. The benefit–cost ratio increased with increasing tank sizes before reaching a plateau. The PBP showed a reverse trend with benefit–cost ratio (Figure 8). The 1st stage can be attributed to the fact that a bigger storage tank is able to store more discharged graywater, thus contributing to higher economic benefit. However, the second stage illustrates that increasing the tank sizes (above 1.2 m³) would not increase the
amount of captured graywater and the corresponding economic benefit, suggesting that further investment for increasing tank size gives no increases in benefit.

Since the economic benefit has been quantified only in terms of reduction of the annual water bills from water supply company, the results of the economical viability analysis performed should be considered conservative. On the one hand, even if relevant, in this analysis the environmental and social benefits have not been taken into account due to limited data availability. For example, benefits of graywater reclamation can obtained by reduce the discharge of treated graywater into natural water bodies (Meneses et al. 2010), since graywater still contains larger amounts of BOD, TN and TP than natural water. Thus, graywater reuse contributes to reduction of contaminants discharge to natural waters (Mahgoub et al. 2010; Lemos et al. 2013). On the other hand, large-scale implementation of graywater recycling in densely urbanized areas may contribute to the reduction of the discharges in the drainage systems (Burns et al. 2015), alleviate pressure on urban drainage systems (Burns et al. 2015; Palla et al. 2017), reduce the size of downstream drainage infrastructure, and may also defer augmentation of mains water infrastructure (Palla et al. 2017). In a climate change perspective, this is a very significant positive feature of graywater recycling (Amos et al. 2018). These neglected aspects would have dis-favoured the economical performance of the graywater recycling system (i.e., leading to the predicted payback periods of this project is longer than actual one).

In addition, another finding of this study is that the benefit–cost ratio of the graywater reuse system is higher when considering higher tap water prices in comparison with the lower tariffs (Figure 10). This outcome indicates that the proposed graywater reuse system might have a greater economic performance in the future, as less water available because of the population growth, contamination, and climate changes (Ding et al. 2017).

This study provides preliminary evidence that the IPSF technology has great potential to been applied in the graywater recycling system of buildings like university apartments which have high residential density and large shower water consumption. The excellent pollutant removal efficiency in graywater treatment may represent a crucial advantage. Moreover, this proposed IPSF system possesses many advantages such as simple design and installation, low operation costs and low energy consumption, and no chemical requirement, which makes this system suitable for decentralized graywater recycling systems in areas where traditional water resources are scarce.

CONCLUSIONS

This work focuses on an innovative decentralized graywater recycling system that combines in one compact unit a settlement process and a filtration phase. The removal efficiency of the IPSF unit using three different filtering materials: manganese sand, quartz sand and light ceramsite were examined, while the economic feasibility of the proposed WWR system was assessed by benefit–cost analysis. Results show that the ceramsite filter presented a superior pollutant removal among three filtering materials, giving 93.3% removal for turbidity, 68.6% for CODcr, 78.9% for NH3-N, and 83.5% for LAS, with effluent quality completely meeting the Chinese Miscellaneous Domestic Water Standard. Economic analysis revealed that the economic feasibility of the WWR system is positively correlated with the price of tap water, this system is financially viable (with BCR higher than 1.0) in regions where local water price is higher than 2.52 CNY/m3. However, some of the environmental and social benefits of the graywater reuse systems cannot be calculated in benefit analysis due to the lack of sufficient data. Future researches are set to provide more comprehensive analysis concerning the benefits of graywater reuse for water authorities and the public to enhance the acceptance of WWR systems. The technology presented in this study offers a option for the enhancement of water security at a building level in many regions.

ACKNOWLEDGEMENTS

This work was financially supported by the Key scientific research project of Guangdong University (characteristic innovation). We would like to thank the staff of laboratory, Zhongkai University of Agriculture and Engineering, for the convenience of this experiment. Many thanks to the anonymous reviewers for their constructive criticisms, which significantly improved the accuracy and quality of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest
DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 5 January 2021; accepted in revised form 27 May 2021. Available online 9 June 2021