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The water treatment and recycling in 105-day bioregenerative life support experiment in the Lunar Palace 1

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ABSTRACT

In the bioregenerative life support system (BLSS), water recycling is one of the essential issues. The Lunar Palace 1, a ground-based bioregenerative life support system experimental facility, has been developed by our team and a 105-day closed bioregenerative life support experiment with multi-crew involved has been accomplished within this large-scale facility. During the 105-day experiment, activated carbon-absorption/ultra-filtration, membrane-biological activated carbon reactor and reduced pressure distillation technology have been used to purify the condensate water, sanitary & kitchen wastewater and urine, respectively. The results demonstrated that the combination of those technologies can achieve 100% regeneration of the water inside the Lunar Palace 1. The purified condensate water (the clean water) could meet the standards for drinking water quality in China (GB5749-2006). The treatment capacity of the membrane-biological activated carbon reactor for sanitary & kitchen wastewater could reach 150 kg/d. During the 105-d experiment, the average volume loading of the bioreactor was 0.441 kgCOD/(m^3d), and the average COD removal efficiency was about 85.3%. The quality of the purified sanitary & kitchen wastewater (the greywater) could meet the standards for irrigation water quality (GB 5084–2005). In addition, during the 105-day experiment, the total excreted urine volume of three crew members was 346 L and the contained water was totally treated and recovered. The removal efficiency of ion from urine was about 88.12%. Moreover, partial nitrogen within the urine was recovered as well and the average recovery ratio was about 20.5%. The study laid a foundation for the water recycling technologies which could be used in BLSS for lunar or Mars bases.

1. Introduction

Bioregenerative life support system (BLSS) is very important to provide indispensable living conditions for astronauts in the manned space activities such as lunar/Mars bases or deeper space exploration, and water recycling is one of the key components for achieving higher closure of BLSS. The types of wastewater in BLSS include the condensate water through the evapotranspiration of higher plants and plant-cultivation substrate, the sanitary wastewater from tooth brushing, bathing, laundry, etc., the kitchen wastewater from food-processing and dining, and other wastewater from equipment operation and human metabolism (sweat, respiration moisture, urine, feces, etc.). The completed treatment and recycling of those different types of wastewater will be of important significance to improve the system closure, reduce supplies from the earth, lower the operation cost, and to create better living environment for the astronauts in long-term space exploration.

Many developed countries have started to study BLSS since early 1960s, and they have basically reached a consensus that in order to put BLSS into practice in space, large-scale experimental BLSS facilities should be built to verify the feasibility and reliability first. Therefore, ground-based experimental BLSSs and related test beds have been constructed and investigated for decades, such as the BIOS series in Russia (the Soviet Union), Bio-Plex in the USA, CEEF in Japan and MELiSSA project led by European Space Agency, in which the water recycling systems have been designed and established by using different technical processes [1–6].

In China, the investigation of BLSS was started late and mainly focused on the key elemental technologies, the conceptual configuration

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design and the simulation modeling of BLSS, etc. [7–11]. A large-scale experimental BLSS needed to be built urgently to verify and consummate the technologies. Therefore, in 2013, a ground-based bioregenerative life support system experimental facility – "Lunar Palace 1" (stage I) was developed by our team, which consists of one comprehensive cabin (42 m^2) for crew's living, animal breeding and waste treatment, and one plant cabin (58 m^2) for plant cultivation. Then, a 105-day closed bioregenerative life support experiment with multi-crew involved was successfully carried out in 2014 [12]. In this experiment, 100% regeneration of the water inside the Lunar Palace 1 has been achieved relying on the high efficient operation of the water recycling system. In this paper, the structure of the water recycling system and its performance during the 105-day BLSS experiment would be introduced specifically.

2. Materials and methods

There were three kinds of wastewater needed to be purified and recycled inside the Lunar Palace 1, including the condensate water from the temperature-humidity control system, the sanitary & kitchen wastewater from the daily life of the crew and the urine. Due to the differences of the contamination level, different wastewater treatment processes should be designed to purify the three kinds of wastewater separately to meet the water quality standards for different usage.

During the 105-day BLSS experiment, the condensate water, sanitary & kitchen wastewater and the crew's urine before and after purification were double sampled and analyzed every 7 days, in order to monitor the water quality and the operation conditions of the wastewater treatment facilities involved in the water recycling system of the Lunar Palace 1. The main continuously monitored indexes of condensate water were chemical oxygen demond (COD_{Mn}), NO_2^--N, NO_3^--N, conductivity, pH, total bacteria and coliform group, the monitored indexes of sanitary & kitchen wastewater were chemical oxygen demond (COD_{Cr}), total nitrogen (TN), total phosphorus (TP), NH_4^+—N and NO_3^--N, and for the urine, the TN and conductivity were tested continuously.

The COD_{Mn}, COD_{Cr}, TN, TP, NH_4^+—N, NO_2^--N, NO_3^--N, total number of bacteria and coliform group were tested according to standard methods [13]. The conductivity and pH were tested using portable conductometer (Hanna Instruments, Inc.) and benchtop pH meter (Mettler-Toledo International Inc.), respectively.

Additionally, when the closed BLSS experiment ran stably, the treated condensate water was sampled and tested by a professional testing agency to verify the quality.

3. Results and discussion

3.1. The design of the water recycling system in Lunar Palace 1

Different wastewater treatment technologies and facilities should be designed and constructed to purify the three kinds of wastewater separately. Moreover, for achieving completed water recycling in system, the purified water should be reasonably distributed and utilized. Therefore, the water recycling system in Lunar Palace 1 was carefully designed and calculated according to our previous conceptual design of a BLSS [14] before its construction. Based on the mass flow design of BLSS and the contamination conditions of each kind of the wastewater, the detailed treatment techniques were determined and the suitable capacity of the treatment facilities could be evaluated.

3.1.1. Treatment method of condensate water

As a key component, the condensate water had the largest quantity in Lunar Palace 1 water recycling system, mainly from the plant transpiration, the plant-cultivation substrate evaporation and the metabolism of the crew. The purified condensate water (the clean water) was partly used as drinking water and sanitary & kitchen water, so it needed to meet the standards for drinking water quality in China (GB5749-2006) [15]. The rest of the clean water was used for the irrigation of the plants. It has been reported that the main contaminants of the condensate water in space station included dissolved organics, ammonia, ions, and microorganisms, which were in a rather high polluted level [16–18]. While the contaminants in the atmosphere of Lunar Palace 1 was highly diluted by the large amount of condensate water from plant transpiration, which reduced the pollution level but increased the quantity of the wastewater. Therefore, activated carbon adsorption combining ultrafiltration and UV disinfection were considered to purify the condensate water due to the high efficiency and large capacity. The process diagram and photos of the condensate water treatment are presented in Fig. 1. The condensate water from temperature-humidity control system was collected in the condensate water tank (equipped with a UV disinfection lamp). Then, the condensate water was pumped through the PP cotton prefiltration column, the activated-carbon adsorption column and the ultrafiltration membrane successively, automatically controlled by the liquid level switch in the condensate water tank. The purified water was stored in the clean water tank for the daily use of the crew members and the plant irrigation (pumped to the nutrient solution tank when needed). The treatment capacity of the facility was 2 L/min.

3.1.2. Treatment method of sanitary & kitchen wastewater

Sanitary & kitchen wastewater from bathing, laundry, food-making and dining was second in quantity to the condensate water but much more polluted, and the main contaminants were high-concentration organic compounds and salts, such as nitrate and sulphate [16,19]. In this experiment, the purified sanitary & kitchen wastewater (greywater) was used to prepare the nutrient solution for the plants. Thus, the greywater should meet the standards for irrigation water quality (GB5084-2005) [20]. Efficient membrane-biological activated carbon reactor was considered to treat this kind of wastewater. In order to prevent the microbial contamination, the bioreactor didn't inoculate any microorganisms from outside the Lunar Palace 1, but naturally inoculated from the atmosphere and the sanitary & kitchen wastewater inside the system as it continuously operated. In addition, ultrafiltration and UV disinfection were added after the bioreactor to prevent the growing microorganisms from polluting the nutrient solution. The process diagram and photos of the sanitary & kitchen wastewater treatment are shown in Fig. 2. The maximum treatment capacity of the membrane-biological activated carbon reactor was designed to be 150 kg/d to fulfill the requirement for 4 crew members.

In order to maintain the persistent disinfection effect during the experiment, all the UV lamps equipped in the water recycling system were kept on 24 h/d.

3.1.3. Treatment method of urine

The treatment and recovery of the crew's urine are the most difficult and critical issues among the water recycling system due to the high concentrations of the salts, urea, ammonia and organics in urine. Many researches have been focusing on the water recycling technologies of the urine for space life support system, including physical/chemical and biological methods [21–23]. In this experiment, reduced-pressure distillation method was considered to treat the urine. Part of the nitrogen would be distilled together with the water vapor, while most of the salts were concentrated, dried and stored. The condensate water from urine (containing ammonia) would be mixed with sanitary & kitchen wastewater and treated by the membrane-biological activated carbon reactor.

Finally, the processes mentioned above were integrated to form the water recycling system in the Lunar Palace 1, and a general scheme of the water recovery procedures during the 105-day experiment was presented [12].

3.2. The performance and analysis of the water recycling system during the experiment

During the 105-day BLSS experiment, the monitoring system

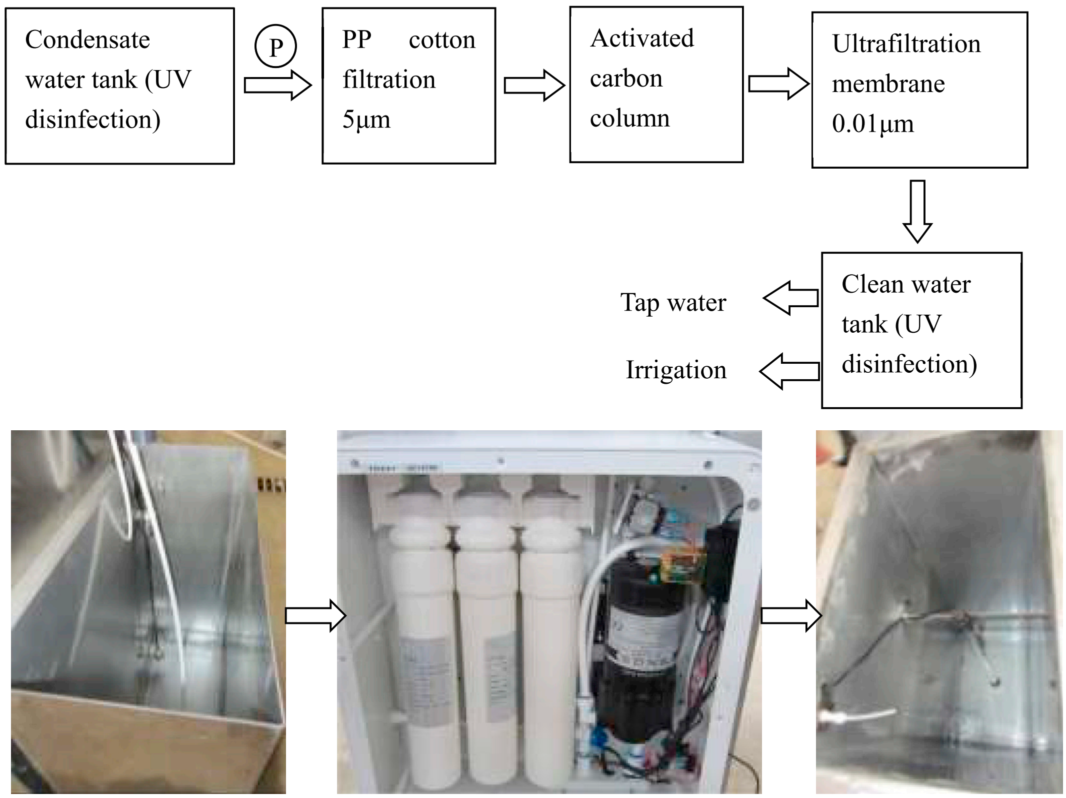

Fig. 1. The process diagram and photos of the condensate water treatment subsystem in the Lunar Palace 1.

automatically recorded the changes of the liquid levels of the clean water tank, the greywater tank and the nutrient solution tank, and the crew measured and recorded the daily use of the water for living in detail based on different purposes and the excreted urine as well, which could be used to calculate the daily water consumption and regeneration. The results showed that the daily water consumption was about 317.04 kg, including 47.24 kg for crew and 269.8 kg for the plant irrigation. The purified condensate water was 270.4 kg/d, and the purified urine and sanitary & kitchen wastewater were 3.01 kg/d and 43.34 kg/d, respectively, which indicated that 100% of water regeneration was achieved [12]. In this part, the performances of the three subsystems for water treatment and recycling were introduced and analyzed.

3.2.1. The performance of the condensate wastewater treatment subsystem

The average values of the continuously monitored indexes of condensate water before and after purification (the clean water) during the experiment are listed in Table 1. The organic contents (COD_{Mn}) were reduced from 3.01 mg/L, which was slightly beyond the concentration limit in drinking water (3 mg/L), to 2.35 mg/L. The treatment efficiency was about 24.2%. The concentrations of NO_3^--N, NO_2^--N and NH_4^+—N in both the condensate water and the clean water were far below the limits. In addition, to further verify the water quality, the clean water was sampled and tested by a professional testing agency during the experiment. Typical indexes were selected considering the standards for drinking water, the original input (tap water) and the characteristics of the whole system (made of stainless steel). The test results (Table 2) showed that the clean water was transparent and without odor and taste. The toxic compounds such as arsenide, cyanide, volatilized phenol, total Cr, Pb, Al and Cu were not detected, except $CHCl_3$ and CCl_4, the concentrations of which were also far below the limits. The existed $CHCl_3$ and CCl_4 were considered from the tap water we used for setting up the system, which were common by-products produced by the drinking water chlorination. The undetected Fe and total Cr indicated that the whole water subsystem mainly made of stainless steel was maintained well and no corrosion happened.

However, the average pH values of condensate water and clean water were 5.83 and 5.90, respectively, which were lower than the lowest limit of the Chinese drinking water standard (pH = 6.5). One reason for this low pH might be the volatile organic acids released by the plants and dissolved to the condensate water, and the other reason might be due to the high concentration of CO_2 (1000–5000 ppm) in the atmosphere of the Lunar Palace 1 [12], which might also partially dissolve to the water. Although the pH of the clean water didn't meet the standard for municipal drinking water, it meet the requirement for international space station, where pH of drinking water should be in the range of 4.5–8.5 [24]. In addition, the chemical analysis results of ISS potable water samples returned from Expeditions 46 through 49 in 2016 showed that the pH values varied from 5.10 to 5.86 [25], which were similar to our results.

The results in Table 1 also showed that no coliform group was detected in the condensate water treatment subsystem, illustrating that the UV-disinfection could efficiently eliminate the coliform. Moreover, the strict separation of the condensate water and sanitary wastewater treatment processes prevented the potential contamination of the condensate water by the coliform group. Finally, aerobic fermentation with a high temperature of 45 °C was applied to treat the feces, which also inhibited the growth of the coliform from fountainhead. However, the total bacteria counts of condensate and clean water were 26000 ± 69941 and 285 ± 343, respectively, showing that some of the airborne microorganisms were concentrated in the water subsystem which was difficult to avoid. Even though the disinfection effect of condensate water treatment devices was as high as 98.9%, the total bacteria count in clean water was still beyond the limit. Thus, further sterilization measure should be applied. In this experiment, the clean water was boiled before it was used as the drinking water of the crew. The cool boiled water was repeatedly sampled and tested for the total bacteria count, and no bacteria were found.

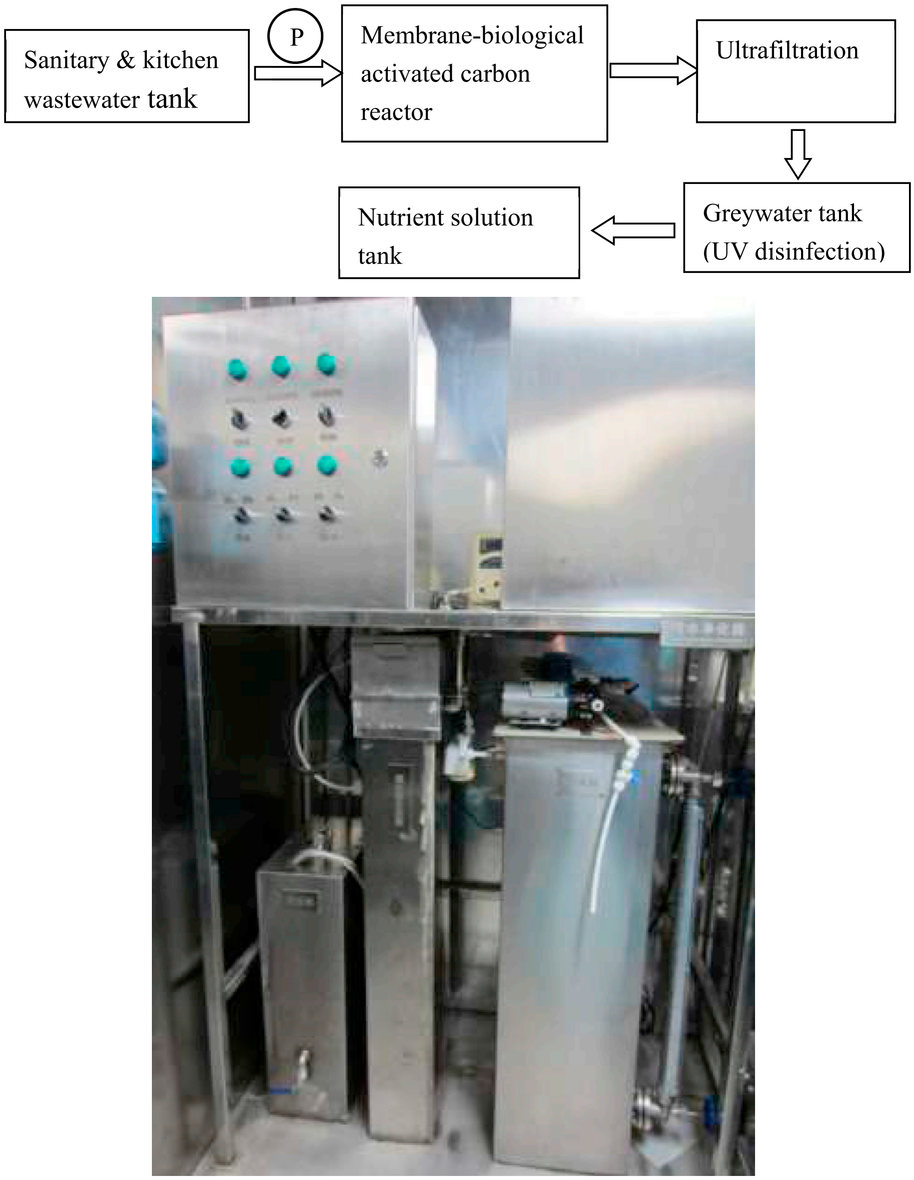

Fig. 2. The process diagram and photos of sanitary & kitchen wastewater treatment subsystem in the Lunar Palace 1.

3.2.2. The treatment and recycling of the sanitary & kitchen wastewater

The concentrations of COD_{Cr}, TP, TN, NH_4^+—N and NO_3^-—N in the raw sanitary & kitchen wastewater and the purified one (the greywater) were tested every 7 days, and the results are shown in Fig. 3. As shown in Fig. 3a, the organic compounds (COD_{Cr}) were reduced significantly from about 557.85 ± 128.33 mg/L to 82.10 ± 41.81 mg/L by the membrane-biological activated carbon reactor, with a removal ratio of 85.3%. Based on the volume and daily treatment capacity of the bioreactor, the average organic volume loading could be calculated as 0.441 kgCOD/(m^3d) in the 105-d experiment. The average COD_{Cr} concentration of the greywater (82.10 ± 41.81 mg/L) was much lower than the limit in the standards for irrigation water (200 mg/L). The concentrations of TP in the sanitary & kitchen wastewater and the greywater were 2.82 ± 0.88 mg/L and 2.33 ± 1.21 mg/L, and the TN concentrations in them were 122.74 ± 41.47 mg/L and 101.57 ± 31.42 mg/L, respectively, as shown in Fig. 3b and c, which demonstrated that the membrane-biological activated carbon reactor would not remove the elements N and P from the water except for the reproduction of the microorganisms. The bioreactor was aerated persistently, thus the denitrification and the biological phosphorus removal which required the alternation of aerobic and anaerobic conditions could not happen. In the Lunar Palace 1, the greywater was used for preparing the nutrient solution of the plants, which should contain N and P. Thus, we considered it appropriate to treat the sanitary & kitchen wastewater without removing the N and P, which could be utilized by the plants subsequently. In this way, the input of nutrients from outside the system could be reduced and the closure degree of the system could be increased.

Additionally, the ammonia nitrogen and nitrate nitrogen concentrations in the greywater were much higher than those in the raw wastewater, especially in the later period of the experiment (Fig. 3d and e), which may result from the enrichment of amminobacteria and nitrobacteria in the bioreactor. These microorganisms could transfer the organic nitrogen in the sanitary & kitchen wastewater to ammonia nitrogen and nitrate nitrogen, which were easier for plant to absorb.

It is also worth noting that the detected parameters including COD_{Cr}, TN, NH_4^+—N at day 91 were at rather high values. It was because the process water in the water-ring vacuum pump used for the reduced-pressure distillation of urine has been added to the sanitary & kitchen wastewater for purification. The process water in the water-ring vacuum pump was rich in nitrogen and organics, which were from the vapor of

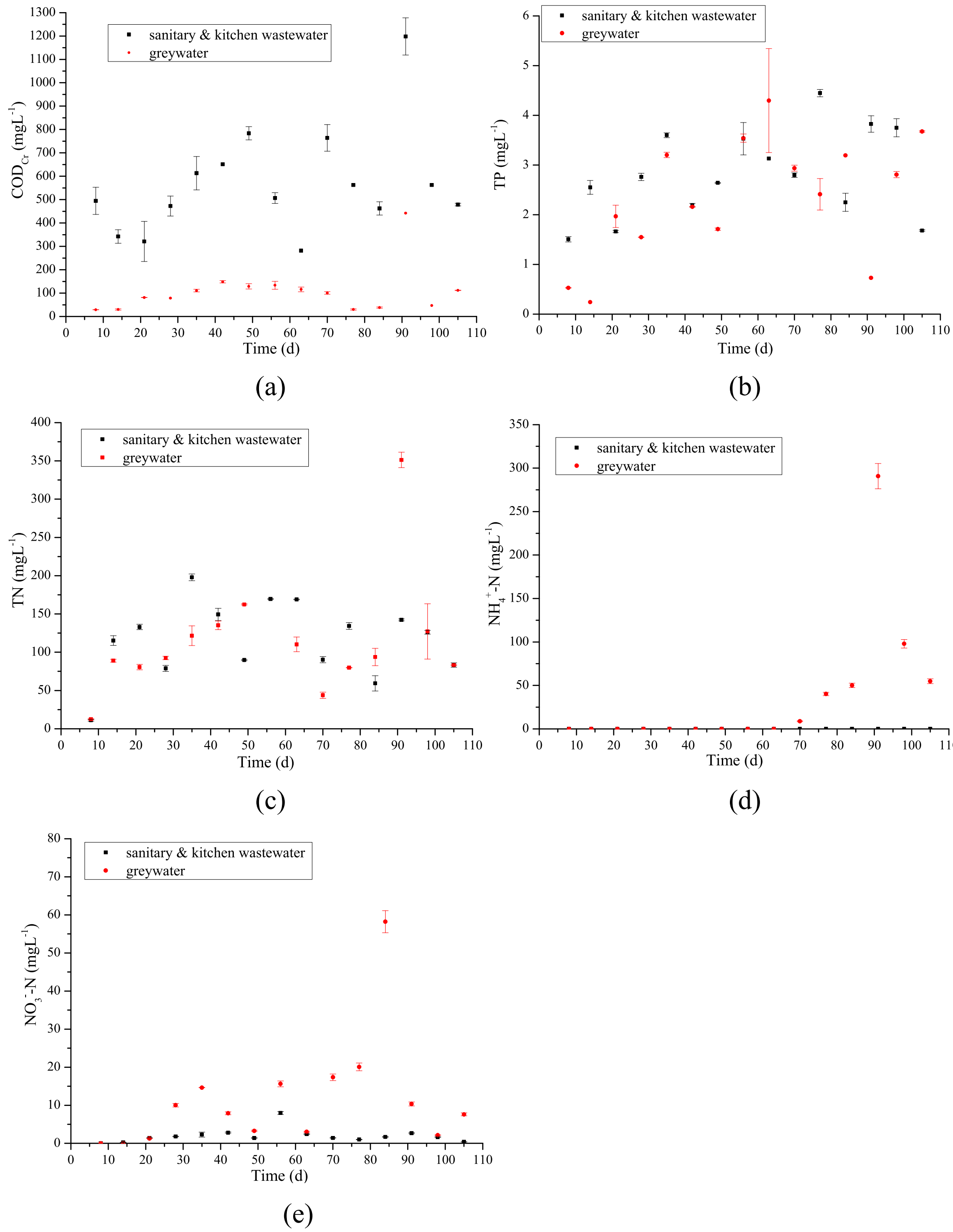

Fig. 3. The removal performance of the membrane-biological activated carbon reactor and the comparison of the concentrations of (a) COD_{Cr}, (b) TP, (c) TN, (d) NH_4^+—N and (e) NO_3^-—N in the sanitary & kitchen wastewater and the greywater.

the urine. Thus, it could be thought of a shock loading on the sanitary & kitchen wastewater treatment subsystem. The results showed that the COD removal efficiency could still reach 63.09% when the COD of influent was up to 1197.96 mg/L, which indicated the excellent anti-shock loading capability of the system. Moreover, the efficiency of the bioreactor could recover to 84.79% right after the shock loading.

3.2.3. The treatment and recycling of the urine in the system

In the Lunar Palace 1, the reuse of urine for irrigation is appropriate, because nitrogen, phosphorus, potassium and other nutrients contained in urine are essential for plant growth. However, the large amount of sodium chloride may lead to the salinization of the substrate, which is negative for the plant growth. Thus, desalination is the first priority. The conductivity of the urine and the condensate from the urine using reduced pressure distillation is presented in Fig. 4. The results showed that the conductivity has been reduced from about 21.21 ± 1.68 ms/cm to 2.52 ± 0.83 ms/cm, with an efficiency of about 88.12%, which could significantly prevent the accumulation of the salts in the plant cultivation system.

The TN concentrations in the urine and in the condensate from urine as well as the daily urine volume of the crew during the experiment are shown in Fig. 5. In the entire experiment, a total of 346 L of the urine has been purified and 100% of the water has been distilled and reused. By the calculation, the total TN content in the raw urine was about 2860 g, while that in the condensate from urine was about 587 g, which meant the total nitrogen recovery efficiency of the reduced pressure distillation was

Table 1
The continuous monitoring indexes and the purification conditions of the condensate water in the experiment.

Parameter	Condensate water	Clean water	Limit[a]
pH	5.83 ± 0.50	5.90 ± 0.45	6.5–8.5
COD_{Mn} (mg/L)	3.10 ± 1.11	2.35 ± 0.43	3
NO_3^--N (mg/L)	0.066 ± 0.041	0.062 ± 0.052	10
NO_2^--N (mg/L)	0.049 ± 0.031	0.045 ± 0.042	1
NH_4^+—N (mg/L)	not detected	not detected	0.5
Coliform group (CFU/100 mL)	not detected	not detected	not detected
Total bacteria count (CFU/mL)	26000 ± 69941	285 ± 343	100
Total bacteria count in the cool boiled clean water) (CFU/mL)	–	0	100

[a] According to the standards for drinking water quality in China (GB5749-2006).

Table 2
The typical indexes of the clean water for water quality test and the results.

Parameter	Clean water	Limit[a]
Cl^-, mg/L	not detected	250
SO_4^{2-}, mg/L	not detected	250
Na^+, mg/L	not detected	200
K^+, mg/L	not detected	–
PO_4^{3-}, mg/L	not detected	–
Arsenide, mg/L	not detected (<0.0010)	0.01
Cr^{6+}, mg/L	not detected (<0.004)	0.05
Pb, mg/L	not detected (<0.0025)	0.01
Cyanide, mg/L	not detected (<0.0025)	0.05
$CHCl_3$, mg/L	0.00288	0.06
CCl_4, mg/L	0.00036	0.002
Turbidity, NTU	<0.5	1
Odor and taste	not detected	not detected
Al, mg/L	not detected (<0.040)	0.2
Fe, mg/L	not detected (<0.045)	0.3
Cu, mg/L	not detected (<0.009)	1.0
Volatilized phenol, mg/L	not detected (<0.002)	0.002
Total Cr, mg/L	not detected (<0.019)	0.05

[a] According to the standards for drinking water quality in China (GB5749-2006).

about 20.5%. In the Lunar Palace 1, the purified urine was also used for preparing the nutrient solution, in which nitrogen is an important element. During the 105-d experiment, about 70770 g (674 g/d) of nutrients for plant cultivation has been introduced to the system from outside [12], which contained 9.72% of the nitrogen, i.e., about 6880 g of nitrogen. Therefore, if all the nitrogen in urine (2860 g) could be

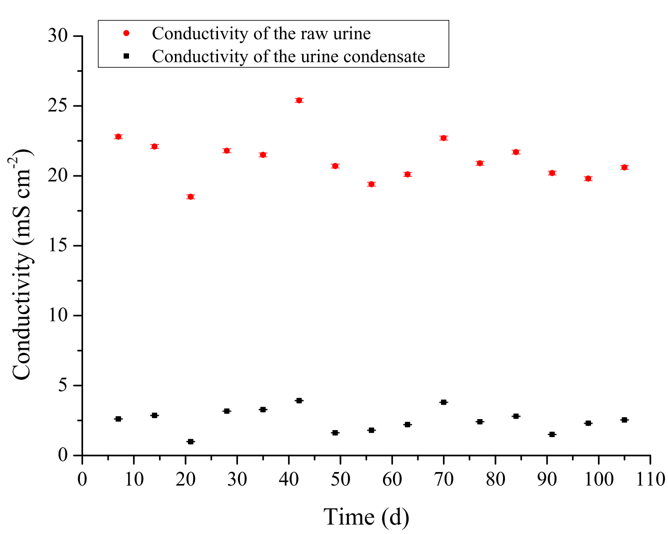

Fig. 4. The conductivity of the urine of the crew and the condensate from urine during the 105-d experiment.

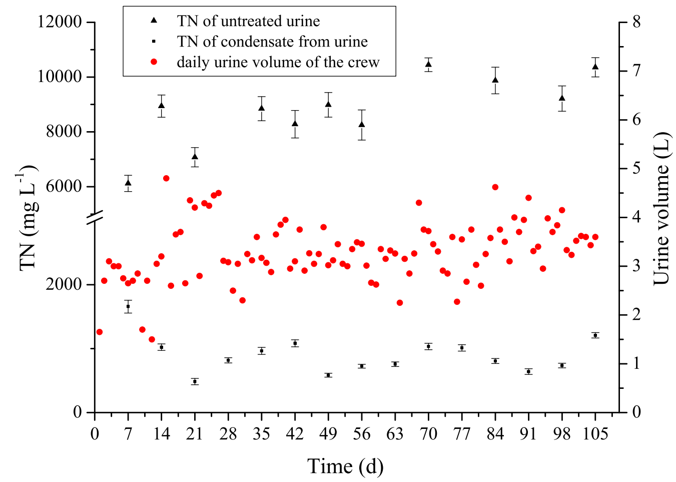

Fig. 5. The TN concentrations in the urine and the condensate from urine as well as the daily urine volume of the crew during the experiment.

recycled simultaneously while desalting the urine, about 33.04% more of the nitrogen supply from outside could be prevented, and the substance circulation and the closure of Lunar Palace 1 could be improved. However, most of the nitrogen in the urine was in the form of urea and other organic forms, such as creatine and uric acid etc., which mainly remained in the residue of the urine. Thus, pretreatment of the urine for the higher recovery of nitrogen has been investigated [26], which might contribute to the further BLSS experiments conducted in the stage II of the Lunar Palace 1.

In addition, it has also been noticed that the TN concentrations in the raw urine slightly increased during the experiment, and we considered it might be due to the change of the diet. It is widely known that Asian diets are particularly rich in refined carbohydrates but low in proteins. It has been reported that the average energy intake percentage from protein of adult residents in Beijing is about 12.6% [27]. However, as shown in our previous work, the daily energy intake percentages of the crew members from protein, fat and carbohydrate were 15%, 28% and 57%, respectively [12]. In which, the percentage of protein was the maximum of the nutritional requirements for ISS Missions [28]. Increasing protein intake would lead to higher excretion of the nitrogenous substances in the urine, such as creatinine [29], which led to the increase of the TN in the raw urine during the experiment.

4. Conclusions

In the Lunar Palace 1, activated carbon-absorption/ultra-filtration, membrane-biological activated carbon reactor and reduced pressure distillation technology were combined together to build the water recycling system, and the condensate water, sanitary & kitchen wastewater and urine were purified separately during the 105-day experiment. The results showed that the combination of those technologies can achieve 100% regeneration of the water inside the Lunar Palace 1. The purified condensate water (the clean water) could meet the standards for drinking water quality in China (GB5749-2006). The treatment capacity of the membrane-biological activated carbon reactor for sanitary & kitchen wastewater could reach 150 kg/d. During the 105-d experiment, the average volume loading of the bioreactor was about 0.441 kgCOD/(m^3d), and the average COD removal efficiency was about 85.3%. The quality of the purified sanitary & kitchen wastewater (the greywater) could meet the standards for irrigation water quality (GB 5084–2005). In addition, during the 105-day experiment, the total excreted urine volume of three crew members was 346 L and 100% of the contained water has been recovered. The removal efficiency of ions from urine was about 88.12%, partial nitrogen within the urine was recovered as well and the average recovery ratio was about 20.5%.

In addition, the insufficient disinfection of the clean water and the rather low recovery efficiency of the nitrogen from the urine have also been concluded in this experiment. Thus, advanced technologies should be studied and applied in the subsequent BLSS experiments conducted in the stage II of the Lunar Palace 1.

Acknowledgments

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