Design suggestions on modified self-sustainable space toilet

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Abstract

The present research investigates the design of compact and lightweight waste collection system (WCS) for interplanetary missions such as Mars, and the Moon as well as the space with the required features of NASA's lunar loo challenge (released date: 25th June, 2020). Existing space toilets' WCS store waste in small plastic bags and these bags are thrown in the space which increases the space junk. If these WCS are used on planets, they could pollute the planets. The newly designed—unisex and self-sustainable space toilet meets its objective of intimacy and warmth for the astronauts as it is equipped with all essential features such as (a) the basin for vomit collection, (b) the rotating waste storage based on the mechanism of artificial gravity, and (c) the noiseless bellow pump for air flow flushing system (AFFS). The WCS is designed for the storage of urine, faeces, vomit, diarrhoea, and menses. In the first half of the research article, the focus is kept on improving self-sustainability of the present WCS. In the second half of the present investigation analyses are done for multiphase flows of the CFD analysis in ANSYS fluent to simulate the flow of air through the nozzle provided with (a) the seat, (b) the urine funnel, and (c) the basin for air flow flushing system (AFFS). The design of the present self-sustainable space toilet proposed herewith is justified suitable for different gravitational conditions such as (a) Mars (3.721 m/s^2), (b) the Moon (1.62 m/s^2), and (c) the zero—or microgravity i.e., the space gravity. The proposed solar-operated WCS could be integrated to function with (a) water recovery and management (WRM) system, (b) the inbuilt composting unit, and (c) the bioregenerative life support system (BLSS). Furthermore, the assessment of the required electrical energy derived from the solar energy (harnessed using efficient solar photovoltaic (PV) modules) is conceptualized for the effective functioning of the present self-sustainable WCS.

Article highlights

- The present investigation explores into the design of lightweight and compact WCS for interplanetary missions such as Mars and the Moon, as well as space missions with the functionality listed by NASA's lunar toilet competition (released date: 25th June, 2020).
- The actual space toilets, which are used on the International Space Station (ISS), are not designed to withstand varying gravity circumstances.
- The new advanced—unisex and self-sustaining space toilet achieves its goal of intimacy and warmth for astronauts by including all necessary features such as (a) a vomit collection basin, (b) rotating waste storage based on artificial gravity mechanism, and (c) a noiseless bellow pump for air flow flushing system (AFFS).

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Abbreviations

AES	Advanced exploration systems
AFFS	Air flow flushing system
ISS	International space station
LR	Logistics reduction
MELiSSA	Micro-ecological life support system alternative
MPCV	Multipurpose crew vehicle
NASA	National aeronautics and space administration
UPA	Urine processor assembly
WCS	Waste collection system
WPA	Water processor assembly
WRM	Waste recovery and management system

1 Introduction

Human space exploration is increasing year after year. Humans could colonize Mars or other suitable satellites such as the Moon. For that purpose, the planet should be habitable to every resource needed for living. One of those essential needs is a waste collection system (WCS) that can work in any gravitational and microgravity conditions. The increasing space exploration demands self-sustainable technology which is fictional for all its requirements [1–3]. The space and planets may lack some essential resources for habitation and interplanetary exploration. Every technology in the space must use minimum resources to function properly. One of those technologies is a WCS as a universal waste management system (UWMS) [4–6].

The focus is to create a lightweight WCS framework that can be used for multiple crewed vehicles and environments in future. The UWMS initiative would lead to a WCS that offers improved crew convenience and quality with reduced build mass and volume. The quality indication device for urine pretreatment that enables water recovery from urine is a key feature of the UWMS. The central hardware of the UWMS is mainly supported by the Advanced Exploration systems (AES) logistics reduction (LR) project [3], with public funding from the Orion-multipurpose crew vehicle (MPCV) project for the second flight group, and the ISS project for ISS-unique technology and deployment hardware for the first UWMS module flying on the ISS [3].

In the absence of gravity, human waste (waste generated after metabolism) collection in a spacecraft during space exploration and any interplanetary mission becomes a challenge. Terrestrial and aircraft commode systems depend on gravity and/or vacuum assist but are not applicable to space flight. In addition, water is a critical asset in space travel and requires separate urine

collection for many extended mission periods to facilitate downstream water restoration. The context of the development of the spacecraft waste collection system (WCS) has been documented previously, so it is useful to briefly study the new hardware solutions [4].

The proposed research focuses on the design of tiny, light-weight WCS for interplanetary missions such as Mars and the Moon, as well as space missions with the features required by NASA's lunar toilet challenge (released date: 25th June, 2020). The waste collection system (WCS) in existing space toilets collects waste in small polythene bags, which are then released into the space, adding to the congestion. The universes may become contaminated if these WCS are used on planets. The proposed self-sustaining space toilet design is justified for a range of gravitational conditions, including (a) Mars (3.721 m/s^2), (b) the Moon (1.62 m/s^2), and (c) the zero- or microgravity i.e., the space gravity in Sects. 2–8. The focus of the second part (Sects. 9–14) of the study remains on enhancing the current WCS's self-sustainability. The suggested solar-powered WCS might be attached to (a) a water recovery and management (WRM) system, (b) a composting unit, and (c) a bioregenerative life support system (BLSS). In addition, the evaluation of essential electrical energy derived from solar energy (harnessed utilizing efficient solar photovoltaic modules) is studied in Sect. 14.3.

2 Basic overview of parts and their functions for various processes of waste handling system

WCS includes a seat to sit and a funnel to collect and direct urination. As shown in Figs. 1 and 2, the design integrates a seat and funnel in such a way that both urination and defecation can be done simultaneously while sitting on the seat, which gives optimum comfort. The optimum dimensions of the assembly are obtained after considering the average human height and volume limitations (0.12 m^3) given in the NASA's lunar loo challenge.

Furthermore, urination can be done separately in any position (standing/ sitting) as the user wants. It provides the user with the flexibility to do their job as they want and to give the best comfort while doing it. The seat and urine funnel are designed in such a way that it directs the matter only in the direction of storage without spreading it all over. Then the faeces and urine are stored in a separate container. For collecting vomit, a basin is designed which rests on the seat, by which, while closing the hole acts as an airlock to avoid any gases to leak whenever it is closed. The vomit from the basin is directed towards

Fig. 1 Schematic representation of different views of waste collection system (WCS). Astronaut doing his/her regular stuff **a** side view, **b** front view, **c** isometric view, and **d** top view

the storage where faeces are stored (there is no need for separate collector).

3 Process considerations

There are different processes (as listed below) to be taken into consideration while designing WCS.

3.1 Process of urination

The urine funnel has a hole of 2 cm diameter that directs the urine to the urine storage via a hose (Table 3). The area of the funnel for capturing urine is 348 cm² with a diameter of 15 cm (Fig. 3). The funnel has a depth of 4 cm. It makes it very wide, which is optimum for collecting and directing the urine. The funnel is designed in

Fig. 2 Design overview and measurements of assembled parts of a WCS. **a** Side view with overall 590 mm length. **b** Front view with overall 390 mm width and 500 mm height. **c** General isometric view. **d** Top view with 400 mm length of commode seat

Fig. 3 Design of a urine funnel—an isometric view

such a way that it does not come in contact with human organs while doing their regular stuff at any position.

Furthermore, the airflow directs the urine to the right spot without spoiling it all over. Due to this contactless urination, there is no need to replace the funnel for each crew member. It can also accommodate both male and female

users without having a separate funnel. This single funnel system reduces the payload and some room space. There is no need for holding the urine funnel while urinating and could be done while standing tall. The urine is stored in a container for some time until the urine is processed and converted into water by the water recovery and management system (WRM) [7].

3.2 Process of defecation

The rectangular seat (Table 3) is 40 cm wide and 40 cm long, which is reasonably large to accommodate various sizes of users. At the centre of the rectangular seat, a centre hole of diameter 15 cm (Fig. 4) is designed, which is a decently sized hole, as it is not too big to compromise the comfort of the user and not too small to become a hurdle in the maintenance and cleaning activities. The seat is provided with some curves to improve comfort by removing the sharp corners. The user can be held on the seat by means of the seat belt.

The seat can be swivelled around an axis to get access to the fecal waste storage whenever maintenance or

Fig. 4 Design of a WCS commode seat—an isometric view

Fig. 5 Design of a basin—an isometric view

cleaning is needed or while jettisoning the waste. The fecal waste storage could be accessed lifting the fecal storage cap (Table 3) attached to the seat. The faeces are converted into fertilizer by using the concept of composting waste which can be used to colonize the planet [8]. The storage for fecal matter can hold weeks of storage until it gets full.

3.3 Process of menstruation

Once, the idea that women might have cycles in space was seen as a reason that astronauts should not be women. We now realize, although the time spans do not affect the potential of a lady astronaut. It could, although be anything lady, astronauts actually do not like to deal around. Fortunately, these days, there are options to protect ladies from getting cycles [9].

3.4 Process of vomitiation

The basin (Table 3) is 30 cm wide and 30 cm long, having a depth of 5 cm, which is wide enough to collect vomit effectively. The area of the basin for collecting vomit is 678 cm². The basin is designed in such a way that it effectively collects the vomit at a single time as shown in Fig. 5. It is

very similar to the basin we have in our home. The vomit when comes out of the mouth it has some velocity and due to the property of surface tension, the vomit sticks to the basin and the airflow from the nozzle guides the vomit to the hole at the centre without spreading it all over the place [5].

4 Working related features

The UWMS design includes a seat, a funnel, and a basin to collect the particular waste as described earlier. Some other parts work together to store the waste for a given period effectively. There are two storages, one for urination and another for defecation. The newly designed pump is used to create a vacuum and to deliver pressurized air. Solenoid valves (Table 3) are used to control the airflow. The entire WCS are contained in a 40 × 50 × 60 cm volume.

While dealing with variations in gravity, it is hard to do the job effectively. The solution is to create a pressure difference. The urination and defecation are forced inside their respective containers by pressurized air, and it is sucked inside the storage by creating a vacuum inside the storage.

The funnel, the seat, and the basin are provided with a set of nozzles around their periphery to force the matter to high-velocity air which directs the waste towards the storage (Fig. 6). The air flow flushing system avoids the spreading of waste all over the place by forcing where it belongs. On the other side, the storage of both fecal matter and urine are provided with a vacuum by a pump to suck the matter inside the storage. The inner surface of the funnel, a hole in the seat, is coated with a hydrophobic coating to avoid the effect of surface tension under low gravity and hence preventing the sticking of any semisolid and liquid waste to the surface [6, 8–11]. Hydrophobicity has an impact. Hydrophobic surfaces repel water, meaning they don't get wet readily when they come into touch with it. The phenomena are caused by surface tension, which is caused by imbalanced molecular forces at the water/solids contact. The hydrophobic coating affects the value of surface tension and thus it was taken into consideration at the time of the CFD analysis. The coating also makes it easy to clean and maintain hygiene.

5 Discussion on microgravity and gravitational conditions

5.1 Defecation under microgravity conditions

It is difficult to store anything in microgravity and even control the flow of any liquid. The artificial gravity is

Fig. 6 AFPS with nozzles. **a** Nozzles for seat. **b** Nozzles for funnel. **c** Nozzles for basin

Fig. 7 Mechanism for collection of defecation at microgravity conditions

introduced to hold the fecal matter in the fecal waste storage through centrifugal force. The fecal waste storage, which stores the defecation, rotates about its central axis and creates a centrifugal force to push everything towards the wall of the storage [12]. The fecal waste storage is covered with a thick plastic bag from inside for ease of cleaning and waste removal (after it is filled) as shown in Fig. 7. The stool sticks to the plastic bag, and the centrifugal force pushes the stool. Due to the centrifugal force, the stool only sticks to the wall of the plastic bag rather than spreading all over the place. The fecal waste storage is protected by a fecal storage casing (Table 3) to avoid any leakage. The plastic bag can be reused (Table 3) after collecting out the fertilized fecal matter to reduce the space junk [12]. When the job is done, the hole on the seat is closed by the basin to create the airlock. The fecal waste storage stops rotating thereafter.

Fig. 8 Mechanism for collection of urination

5.2 Urination under microgravity conditions

The storage for urination does not require such centrifugal force because it is kept at a distance from the urine funnel, and non return valves are present to avoid any backflow of urine. Inside the storage, there are urine filters which could be accessed by lifting the urine storage cap (Table 3). The filters will remove the contaminants from the urine as shown in Fig. 8. The urine sticks to the surface of the filter material and stays in the container due to the effect of surface tension. The opening for vacuum is kept at a distance away from the filter, which prevents the urine to flow inside the pump. When the storage is filled, the urine could be extracted from the inlet opening of the storage through a vacuum pump.

5.3 Under gravitational conditions

In gravitational conditions, things are easily settled. As the mechanism of artificial gravity could be turned off to hold fecal matter and save energy. The pressurized air and vacuum are enough to do the required task [12–14].

6 Disposal of waste after a regular interval

The semisolid wastes such as stool, diarrhoea, and vomit are stored in the same container having a volume of $17,671 \text{ cm}^3$. The storage container can accommodate 18 kg of waste matter. If it will be 500 g of fecal matter per use and two uses per day, then for 14 days, it amounts to 14 kg [10]. The storage container is thus, good enough for the requirement and could store additional wastes such as diarrhoea and female menses as well as hygiene products. Furthermore, there is no need to replace the storage container for defecation. For liquid waste such as urine, the volume of storage is $15,245 \text{ cm}^3$ which can accommodate 15 L of urine in each filter unit. There are two units inside the storage, as described earlier, and these two filter units will have a total capacity up to 30 L. If it will be 1 L of urine per use and six uses per day, then for 14 days, it amounts to 84 L [10].

7 Noise reduction

A pump is designed which is quiet in operation, and it uses the vacuum of the space. Three different chambers are considered in the design. The casing of the pump (Table 3) is designed with light weight and anticorrosive aluminium alloy 7075. The first chamber is opened to the vacuum of the space and the remaining two are connected to the system. Due to the pressure difference, the bellows (Table 3) expands towards the vacuum chamber, bringing air from the system into the second chamber. Afterwards, the bellows are brought back to its original position by a motor, delivering the air from the second chamber with a pressure rise.

The pump acts as a compressor and it has non return valves (Table 3) to control the airflow. The air is displaced only by bellows, which prevents air from leaking out of the cabin and avoiding astronauts exposing to the vacuum (Fig. 9). The vacuum chamber has a solenoid valve, which only opens when we turn on the pump for safety. The bellows works quite silently, but it will be rigid at low temperature around -270°C . The silicon rubber can withstand the low-temperature operation [11]. If the above bellows arrangement fails to perform, then a piston and cylinder setup is designed alternatively, where the piston acts as a

Fig. 9 An insight into the bellows pump with its functional parts

separator. It may induce some noise, but it (noise) can be prevented by foam padding.

8 Safety for not being exposed to vacuum

The most dangerous part of the system is the vacuum chamber of the pump, which is connected to the hard vacuum of the space [15]. For safety, a solenoid valve has been provided for that chamber, which only opens when the pump is turned on. However, in the case of emergency, the vent, which connects the vacuum of the space to the system, must have another solenoid valve to make sure no air escapes in case of system failure. The pump does not have much power to create a hard vacuum, which could damage the astronauts. Its main focus is to create a vacuum and pressurized air at the same time. The method creates a more substantial pressure difference across the system without the need to create a hard vacuum, which could be dangerous.

9 A few suggestions for the effective implementation of the proposed space toilet for interplanetary missions such as Mars, and the Moon as well as the space towards the fulfilment of the prime objectives such as its self-sustainability

A good toilet requires too many resources to be comfortable for one to use. To prevent carrying a lot of resources to the mission as well as to save room in the spacecraft and reduce its weight, it is always suggested to design a self-sustainable toilet which could support the in situ resource management (ISRM) program [16–19]. For a self-sustainable toilet, it has to provide sustainable living in

which nothing is consumed except what is produced by the system. To be a toilet self-sustainable one, it has to consume nothing but only renewable resources such as water, electricity, etc. As discussed earlier, the presented WCS does not use water for its function, and the electricity can be generated using solar panels (provided to the space station or lander). The WCS has to work only with solar energy. The waste produced by humans such as urine and faeces must be converted into reusable matter. Nowadays, due to lack of water, treatment and reuse of human urine is increasingly adopted here on Earth, and it is always been a priority for space missions. The composting toilet ideas are widely welcomed for self-sustainable living in the tiny house movement. Although it requires some additional accessories but human urine can be converted into water and oxygen, and the faeces can be used as a fertilizer and as a farming resource for the habitation of the uncolonized planet [16–19]. By adding these accessories,

the crew members can get hygiene water, drinking water, and some useful nutrients from urine.

10 Current water recovery and management system (WRM) is used on the ISS for the treatment of waste water

The most important resource in space is water, a reliable, robust water recovery system is the most important in human space exploration. The water recovery and management (WRM) system used on the ISS makes sure the availability of water for drinking and hygiene purposes, oxygen production, and urine. The primary sources of water are hygiene, urine, sweat from crew members, and condensed water vapour from crew respiration. Figure 10 shows the schematic diagram of WRM which is used with the ISS. Besides the waste water produced by the

Fig. 10 Schematic block diagram showing all **a** the accessories of the urine processor assembly (UPA), and **b** the water processor assembly (WPA) used by the ISS (reprinted with permission from Ref. [16], Copyright 2020 MDPI)

astronauts, the WRM receives the water produced from the carbon dioxide reduction system [16]. The carbon dioxide reduction system uses the Sabatier technology [16] to regenerate water from CO_2 and H_2 . The chemical reaction is shown in Eq. (1). The proposed space toilet could be used for biomineral activities. The Martian regolith could be used to extract iron ore for construction activities needed to colonize the planet, and carbon dioxide to support plant lives, and indirectly human lives. The biomineral activities are initiated through addition of the specific algae, *Chlorella vulgaris* (4 g) in biomass [20].

In the above Eq. (1), CO_2 , H_2 , CH_4 , and H_2O are carbon dioxide, hydrogen gas, methane gas, and water vapour molecules, respectively. The chemical reaction is carried out in a pressurized chamber maintained at high pressure around 30 bar and at elevated temperature around 300–400 °C where nickel catalyst is used to boost the reaction [21].

The water recovery and management system are subdivided in two sections (a) urine processor assembly (UPA) and (b) water processor assembly (WPA) [16]. The urine collected from crew members in the space has more concentrations of calcium, uric acid, cystine, struvite, calcium oxalate, and calcium phosphate than that of the same collected on Earth. It is due to changes of bone stresses in microgravity conditions, reduced fluid intake, presence of nanobacteria, and hypercalciuria. Higher level concentration of these elements in a human body can cause the physiological issue. It can promote diseases like kidney stones. Although there is a lack of water resources for us in the space, it is necessary to recirculate the fluids through the body continuously for better health, and one needs water for other hygiene purposes. Therefore, reusing the processed urine and waste water completes the loop of the recycling process. The processing of conversion of human urine into usable water is done in UPA and WPA [16]. Urine is treated by UPA, while WPA treats the water with condensate, hygiene, Sabatier products and water from the UPA.

10.1 Urine processor assembly (UPA) is used by ISS to stabilize urine and convert it into distilled water

Urine is an aqueous solution of more than 95% water, with constituents such as urea ($\text{CH}_4\text{N}_2\text{O}$)—9.3 g/L of urine, chloride (Cl^-)—1.87 g/L of urine, sodium (Na)—1.17 g/L of urine, potassium (K)—0.750 g/L of urine, creatinine ($\text{C}_4\text{H}_7\text{N}_3\text{O}$)—0.670 g/L of urine, and other

dissolved ions, organic and inorganic compounds such as proteins, hormones, metabolites, so on and so forth [22].

In the UPA, initially, urine is to be stabilized chemically, and it is done by storing it with the mixture of phosphoric acid (H_3PO_4), and chromium ions (Cr^{6+}) in a wastewater storage tank assembly (WSTA). Secondly, when the sufficient amount of urine is collected, it is passed through the distillation assembly (DA). The DA unit uses a low-pressure vapour compression and evaporation system to enhance the urine distillation process. The distillate is then passed to the gas separator to separate the purge and trapped gases. Furthermore, the liquid is served under various UPA sensors and effectors which monitors and sends the data to an online monitoring system. After checking the concentration levels, it is passed to the water processor assembly (WPA) [16].

Earlier until 2016, when the urine was treated with sulphuric acid (H_2SO_4), the recovery rate was only 70–75%. To compensate for the higher concentration of calcium sulphate (CaSO_4) which is formed by higher concentration of calcium in the urine, sulphuric acid (H_2SO_4) was replaced with phosphoric acid (H_3PO_4). It would increase the urine recovery rate up to 85% [16].

10.2 Water processor assembly (WPA) to be used by the ISS to collect distilled water from the UPA and waste hygiene water for filtration

The distilled water obtained from the UPA cannot be directly used for drinking or hygiene purposes. It requires further processing, and that is done in the WPA. As soon as water enters the WPA, it is passed through a series of accessories such as temperature control system, humidity control system, and gas/liquid separator, after which it is ready to be passed through multi-filtration beds. In such type of filters, nonvolatile organic and inorganic compounds are extracted. Then the water is passed to the catalytic reactor, in which the organics have low molecular weight gain gaseous oxygen at 130 °C [16]. Furthermore, the water is again passed through the gas/liquid separator to remove extra oxygen and gaseous by-products. The ion-exchange bed removes carbonate and bicarbonate ions produced during oxidation, and the required iodine is provided which is needed for microbial control. Finally, the heat from catalytic oxidation is recovered by the regenerative heat exchanger. The water we get is useful for hygiene purposes, and after further testing and mineralizing, the water will be used for drinking purposes [16].

10.3 Limitations of the waste management systems used on the ISS nowadays are as follows

- The maximum water recovery of the system is badly affected by the high calcium content in the urine of the crew members, which causes calcium sulphate (CaSO_4) precipitates on the distillation assembly of the UPA.
- To lower the pH of the urine, strong inorganic acids are used which causes corrosion in the distillation units.
- The WCS store semisolid waste in small plastic bags and these bags are thrown away in the space which increases the space junk.

11 Composting of fecal matter for waste utilization purposes

Composting process of waste matter is the same in space as on Earth. The main purpose of composting in the space is waste utilization. As we know, astronauts need to travel a lot distance consuming a number of days or weeks, due to this approximately 14 kg (maximum) of fecal matter is collected per week for 2 persons, adding other wastes like waste food, vomit, toilet paper and sanitary pads it will be up to 17 kg (maximum) [10]. Throwing these wastes in the space increases the space junk and pollutes it. Thus,

instead of only storing the waste, the composting process should be initiated through the in situ resource management (ISRM) program in the space itself, and could be used to support plant life wherever the conditions are favorable. The end product of the composting process can be used as soil conditioners.

Composting is a biological process in which human waste (faeces) and inedible biomass are converted into a chemical and physical form which is compatible for fertilizing the soil and enhancing crop growth. Mesophilic composting is a total dry process, so water or urine is not to be mixed with faecal waste. Although there are various composting methods, as it is essential to save water in the space, the mesophilic composting process can be used. In this process, the organic waste is decomposed and turns human waste into compost-like material, but it does not destroy all bacteria. The ratio between carbon content and nitrogen content (C:N ratio) which is best for composting is between 25:1 and 30:1. When the C:N ratio is given limit, the decomposition starts rapidly. Composting process is carried out by microorganisms like bacteria, fungi, and mesophile under aerobic conditions. Therefore, this process takes longer time and needs to be stored in a closed composting chamber which is the same container used to store the fecal matter as shown in Fig. 11. The process is to

Fig. 11 A schematic diagram of a composting chamber located inside the toilet sealed to prevent unpleasant smell

be carried out on the waste having minimal moisture content (between 50 and 55% and pH of 6.98) because moisture promotes the pathogenic germs growth and odour. 60% of the total weight of compostable waste is lost due to moisture reduction and carbon dioxide which also increases the total waste storing capacity of the container. Pathogenic terms and potential odour for longer time increases the risk of disease for crew members. Therefore, to reduce the moisture content in the waste, some waste additives such as sawdust, coconut coir, paper, and used sanitary pads can be stored in the same chamber (approx. 15–20% of additives are added). Adding these not only reduces the waste, but also promotes aerobic decomposition and improves carbon-to-nitrogen ratio. After successful reduction of moisture, the waste is again stored for a long time (at 55–60 °C, for 3 days) to let the pathogenic germs die off. Now, we get some humus-like end product, which is mixed with soil. Humus is a dark organic matter that forms in soil after the death of plants and animals. Humus is very nutritional for Earth's soil, it improves the health of soil, mostly adds nitrogen into the soil which is required for the growth of plants [18, 19].

The whole process of composting is done in the spacecraft, and then the compost is used to grow some edible plants which are used to feed the crew and helps creating oxygen and removing carbon dioxide from the air. Composting process requires 4–5 weeks for the conversion of compostable waste to compost at the rate of 6–7% [23].

12 Project MELiSSA (micro-ecological life support system alternative)

For self-sustainable toilets, the concept of bioregenerative life support system (BLSS) is used. In 1987, the European space agency (ESA) visualized a project to create a BLSS which can be used on the ISS. That started interdisciplinary collaboration projects such as MELiSSA [24]. The core concept of MELiSSA project is recreating an artificial ecosystem which is capable of producing oxygen, water, and food by recycling the waste which is produced by the crew members in a space ship (organic waste, urine, faeces and CO₂). It has 5 compartments which are interconnected to each other and operates independently. These compartments are colonized by anaerobic thermophilic bacteria, photoheterotrophic bacteria, nitrifying bacteria, photoautotrophic bacteria, and superior plants. As Fig. 12 shows, a specific function is assigned to each compartment to transform the waste into supplies.

12.1 Compartment 1 (liquefying compartment/ microbial fuel cell)

Compartment 1 (Fig. 13) collects all waste from the spaceship/ space station (i.e., urea, kitchen waste) and some non-consumable portions of plants (i.e., straw and roots). The compartment anaerobically transforms the waste into ammonia, hydrogen (H₂), carbon dioxide (CO₂), volatile fatty acids, and minerals. The compartment operates in thermophilic conditions (55 °C) for

Fig. 12 Project MELiSSA BLSS cycle showing compartment 1 (liquefying compartment/ microbial fuel cell), compartment 2 (photoheterotrophic compartment), compartment 3 (nitrifying compartment / membraned aerated biofilm reactor), compartment 4 (photoautotrophic compartment), and compartment 5 (crew compartment) with flow process (reprinted with permission from Ref. [16], Copyright 2020 MDPI)

Fig. 13 A schematic details of the microbial fuel cell with its chemical reaction are carried out in compartment 1

biosafety and to achieve optimum degradation efficiency. Proteolysis, saccharolysis, and cellulolysis carry the process of degradation. The reaction produces some electrical energy that can be used to power small things.

12.2 Compartment 2 (photoheterotrophic compartment)

Compartment 2 eliminates the terminal products of the liquefying compartment; especially the volatile fatty acids. The volatile fatty acids are transformed into a source of organic carbon under anaerobic conditions with the help of photoheterotrophic bacteria growth. Photoheterotrophic bacteria growth process uses light as an energy source.

12.3 Compartment 3 (nitrified compartment/ membraned aerated biofilm reactor)

The main function of compartment 3 (Fig. 14) is to cycle ammonium ions (NH_4^+) produced from waste to nitrates. These nitrates are the most favourable source of nitrogen for the superior plants and bacteria in compartment 5. The compartment is composed of a mixture of *Nitrosomonas europaea* bacteria, which oxidises ammonia and *Nitrobacter winogradskyi* which oxidises nitrates. Both use carbon dioxide (CO_2) as a source of carbon.

12.4 Compartment 4 (photoautotrophic compartment)

Compartment 4 (Fig. 15) transforms carbon dioxide into oxygen, which creates edible biomass that can be used for feeding the crew and for water recovery. It is divided into

Fig. 14 A schematic detail of the membraned aerated biofilm reactor with its chemical reaction is carried out in compartment 3

Fig. 15 A schematic detail of the photobioreactor and superior plants with its chemical reaction is carried out in compartment 4

Table 1 Constituents of edible biomass

Constituents	Percentage (%)
Proteins	61 ± 9
Carbohydrates	13.4 ± 0.6
DNA	3.2 ± 0.8
RNA	3.6 ± 0.4
Chlorophylls	0.30 ± 0.02
Phycocyanin	7 ± 2

two subcompartments (4a and 4b). The sub-compartment (4a, photobioreactor) is colonised by photoautotrophic *Arthrospira platensis* bacteria which produces water and oxygen by using light as a source of energy and carbon dioxide (CO₂), as a source of carbon. The biomass created here is edible so it can feed the crew. Sub compartment (4b) is colonised by selected superior plants that do the same role as photoautotrophic bacteria. These superior plants transform carbon dioxide (CO₂) into oxygen at a greater specific speed than photoautotrophic bacteria. The composted human waste can be used as a fertilizer for these superior plants which further utilizes human faeces for their growth.

The biomass processed in the chamber is sufficient to provide foods for the crew members. The edible biomass has constituents [25] as listed in Table 1.

12.5 Compartment 5 (crew compartment)

Compartment 5 is made up of crew members which transforms food, water, and oxygen into faeces, urine, and CO₂ which completes the cycle. MELiSSA project along with the presented WCS can be used on spaceships and other planets like mars for self-sustainable living. It could be helpful

to colonize planets like mars. It closed the loop of the artificial ecosystem which could be beneficial for all future space missions for improved living with minimum waste.

13 Bioreactor to create sustainable living for humans on mars

When the spaceship is travelling, the composting process and bioregenerative life support system (BLSS) is used for waste utilization, but when it lands on any planet like Mars, the process of biological reaction (bioreaction) can be employed to support the life system on Mars by creating oxygen from the human waste. As we know, Mars is the closest planet after Earth that could host life. To do so, it is required to grow algae and edible plants on Mars, that produces oxygen, fruits, and vegetables required for humans to be alive. The main advantage of growing plants on Mars is that it requires less water than that of Earth, it is due to the lower gravity because of which the water on the surface is not drained off quickly. The bioreactor compartments (Fig. 16) feed each other and help to convert human waste into biomass which is rich in nitrogen, protein, and carbohydrates.

Initially, algae which is bought from Earth is left in the open to get sunlight and nutrients to grow. When generating nutrients for the biomining process, algae, using sunlight transform carbon dioxide to oxygen using photosynthesis process as discussed in Eq. (2).

In the above Eq. (2), CO₂ is carbon dioxide in gaseous state, H₂O is water, O₂ is oxygen in gaseous state, C₆H₁₂O₆ is sugar (glucose).

Fig. 16 A schematic representation of bioreactor systems (BSs) for biomining activities on Martian soil (regolith) (reprinted with permission from Ref. [26], Copyright 2020 Elsevier)

Furthermore, the biomass released from the algae, when mixed with Martian soil (regolith) and lactate biomining process starts. Lactate is actually a cell metabolism that is created after algae convert nutrients to biomass. In the biomining process, bacteria are produced in biomass which is mixed with regolith, so that the plants can consume more amino acids to speed up their growth.

Finally, the treated regolith is used to grow edible plants. Carbon-dioxide requirement of the plant is fulfilled by left-over of the biomining process, and, Mars has excess carbon dioxide. The edible plants that are grown after this process provide fruits, vegetables, and oxygen to humans. Hydrophobic coating liquid-entrenched smooth surface (LESS) which can last for 500 flushes [27]. After that, more silicon coating is to be applied with the help of spray.

14 Results and discussions

14.1 The multiphase flows model for AFFS

The analyses are done in multiphase flows of the CFD analysis in ANSYS fluent. Equations [(1)–(8)] are used in ANSYS for multiphase flows [28]. In such type of analysis, the whole volume of the model is considered as fluid. The fluid could be stationary or moving. To get a fluid flow, some part of the volume is allowed to move involving boundary conditions. Streamlines are the lines travelled by neutrally buoyant particles in equilibrium with the fluid motion. Streamlines are an excellent tool for visualization of complex three-dimensional flows. In such case, we have emphasized streamlines to examine the flow around and in the wake of the module.

For multiphase flows, Ansys Fluent solves transport equations for scalars such as per phase and mixture. For an arbitrary scalar, ' k ' in phase I , denoted by ' ϕ_I^k ', the Ansys Fluent solves the transport equation inside the volume occupied by phase I as shown in Eq. (3) [28].

$$\frac{\partial \alpha_I \rho_I \phi_I^k}{\partial t} + \nabla \cdot (\alpha_I \rho_I \vec{u}_I \phi_I^k - \alpha \Gamma_I^k \nabla \phi_I^k) = S_I^k \quad k = 1, \dots, N \quad (3)$$

where α_I , ρ_I , and $\vec{u}_I$ are the volume fraction, physical density, and velocity of phase I , respectively. The parameters such as Γ_I^k and S_I^k are used to represent the diffusion coefficient and source term, respectively, in the above Eq. (3). In such a case, scalar, ϕ_I^k is associated with phase I only, and here it is taken as an individual field variable for the phase [28].

The mass flux for phase I is defined using the function, ' F_I ' as shown in Eq. (4) [28].

$$F_I + \int_S \alpha_I \rho_I \vec{u}_I d\vec{S} \quad (4)$$

In above Eq. (4), $d\vec{S}$ is the vector area of the face. In case of the transport variable described by a scalar, ' ϕ_I^k ' represents the physical field which is shared between phases, or is considered the same for each phase, then the scalar should be considered as being associated with a mixture of phases, ' ϕ^k ' [28]. In such case, the generic transport equation for the scalar is expressed using Eq. (5).

$$\frac{\partial \rho_m \phi^k}{\partial t} + \nabla \cdot (\rho_m \vec{u}_m \phi^k - \Gamma_m^k \nabla \phi^k) = S_m^k \quad k = 1, \dots, N \quad (5)$$

In the above Eq. (5), the parameters such as mixture density, ' ρ_m ', mixture velocity, ' $\vec{u}_m$ ', and mixture diffusivity for the scalar, ' Γ_m^k ' are substituted using the set of Eqs. (6)–(10) [28].

$$\rho_m = \sum_I \alpha_I \rho_I \quad (6)$$

$$\rho_m \vec{u}_m = \sum_I \alpha_I \rho_I \vec{u}_I \quad (7)$$

$$F_m \vec{u}_m = \int_S \rho_m \vec{u}_m d\vec{S} \quad (8)$$

$$\Gamma_m^k = \sum_l \alpha_l \Gamma_l^k \quad (9)$$

$$S_m^k = \sum_l S_l^k \quad (10)$$

14.2 Analysis of the air flow through AFFS under various conditions

The multiphase flows is used for different cases such as (a) flow of air through the nozzle provided with the seat, (b) flow of air through the nozzle provided with the urine funnel, and (c) flow of air through the nozzle provided with the basin. The air flow simulations through AFFS are analyzed using default and fine tetrahedron meshes.

14.2.1 Case I: Flow of air through the nozzles provided with the seat

The air flow simulations through AFFS for the seat are shown in Fig. 17, where the flow pattern of air and fecal matter can be analyzed. The air enters through the air inlet provided with the seat. The air circulated through the tubing designed along the periphery of the centre hole of diameter 15 cm (Fig. 4). The tube has a set of nozzles designed at an angle of 45° with respect to the XY plane in the vertical downward direction (Z-axis) to drift the air flow with a velocity of 8 m/s. The air flow distributes along the set of nozzles to flush the fecal matter into the fecal waste storage. The fecal matter enters into the centre of the opening as they are flushed with air at a high velocity around 8 m/s towards the fecal waste storage. Figure 17 shows the particle traces (features available with Ansys Fluent) of AFFS for the seat. For ease of calculation and to reduce the computational effort; a cut section of the seat is used for the analysis. The analyses are carried out for different gravitational conditions of (a) Mars (3.721 m/s^2), (b) the Moon (1.62 m/s^2), and (c) the zero- or microgravity i.e., the space gravity.

The fecal matter velocity changes according to the different gravitational conditions considered as shown in Fig. 17. The flow patterns of (i) air through the nozzles of AFFS, and (ii) fecal matter are similar for the gravitational conditions of (a) Mars (3.721 m/s^2), and (b) the Moon (1.62 m/s^2). The velocity of air through the nozzles of AFFS varies up to 9.608 m/s to simulate the flow of fecal matter through the flushing speed up to 9.608 m/s during interplanetary missions such as Mars exploration, and the Moon exploration (Fig. 17a, b). The velocity of air through the nozzles of AFFS varies up to 15.06 m/s to simulate the flow of fecal matter through the flushing speed up to 15.06 m/s during space missions (Fig. 17c).

14.2.2 Case II: Flow of air through the nozzles provided with the urine funnel

The air flow simulations through AFFS for the urine funnel are shown in Fig. 18, where the flow pattern of air and urine can be analyzed. The air enters through the air inlet provided with the urine funnel. The air circulated through the tubing designed along the periphery of the urine funnel (Fig. 3). The tube has a set of nozzles designed at an angle of 55° with respect to the XY plane in the vertical downward direction (Z-axis) to drift the air flow with a velocity of 8 m/s. The air flow distributes along the set of nozzles to flush the urine into the urine storage. The urine is flushed with air at a high velocity around 8 m/s towards the urine storage. Figure 18 shows the particle traces (features available with Ansys Fluent) of AFFS for the funnel. The analyses are carried out for different gravitational conditions of (a) Mars (3.721 m/s^2), (b) the Moon (1.62 m/s^2), and (c) the zero- or microgravity i.e., the space gravity.

The fecal matter velocity changes according to the different gravitational conditions considered as shown in Fig. 17. The flow patterns of (i) air through the nozzles of AFFS, and (ii) urine are similar for the gravitational conditions of (a) Mars (3.721 m/s^2), and (b) the Moon (1.62 m/s^2). The velocity of air through the nozzles of AFFS varies up to 10.03 m/s to simulate the flow of urine through the flushing speed up to 10.03 m/s during interplanetary missions such as Mars exploration, and the Moon exploration (Fig. 18a, b). The velocity of air through the nozzles of AFFS varies up to 13.6 m/s to simulate the flow of urine through the flushing speed up to 13.6 m/s during space missions (Fig. 18c).

14.2.3 Case III: Flow of air through the nozzles provided to the basin

The air flow simulations through AFFS for the basin are shown in Fig. 19, where the flow pattern of air and vomit can be analyzed. The air enters through the air inlet provided to the basin. The air circulated through the tubing designed along the periphery of the basin (Fig. 5). The tube has a set of nozzles designed at an angle of 20° with respect to the XY plane in the vertical downward direction (Z-axis) to drift the air flow with a velocity of 8 m/s. The air flow distributes along the set of nozzles to flush the vomit into the fecal waste storage. The vomit enters into the centre of the opening as they are flushed with air at a high velocity around 8 m/s towards the fecal waste storage. Figure 19 shows the particle traces (features available with Ansys Fluent) of AFFS for the basin. For ease of calculation and to reduce the computational effort; the cut section of the basin is used for the analysis. The analyses are carried out for different gravitational conditions of (a)

Fig. 17 The air flow simulations through nozzles provided with the seat (40 cm wide and 40 cm long) are done for three different conditions such as **a** for Mars gravity (3.721 m/s^2), **b** for the Moon gravity (1.62 m/s^2), **c** for the zero- or microgravity i.e., the space gravity. The fecal matters are flushed with air at a high velocity around 8 m/s towards the fecal waste storage. The CFD analyses are carried out to study flow patterns of (i) air through the nozzles of AFFS, and (ii) fecal matter

Fig. 18 The air flow simulations through nozzles provided with the urine funnel are done for three different conditions such as **a** for Mars gravity (3.721 m/s^2), **b** for the Moon gravity (1.62 m/s^2), **c** for the zero—or microgravity i.e., the space gravity. The urine is flushed with air at a high velocity around 8 m/s towards the urine storage. The CFD analyses are carried out to study flow patterns of (i) air through nozzles of AFFS, and (ii) urine

(a)

(b)

(c)

Fig. 19 The air flow simulations through nozzles provided to the basin are done for three different conditions such as **a** for Mars gravity (3.721 m/s^2), **b** for the Moon gravity (1.62 m/s^2), **c** for the zero- or micro-gravity i.e., the space gravity. The vomit is flushed with air at a high velocity around 8 m/s towards the fecal waste storage. The CFD analyses are carried out to study flow patterns of (i) air through the nozzles of AFFS, and (ii) vomit

Mars (3.721 m/s^2), (b) the Moon (1.62 m/s^2), and (c) the zero- or microgravity i.e., the space gravity.

The fecal matter velocity changes according to the different gravitational conditions considered as shown in Fig. 17. The flow patterns of (i) air through the nozzles of ADFS, and (ii) vomit are similar for the gravitational conditions of (a) Mars (3.721 m/s^2), (b) the Moon (1.62 m/s^2), and (c) the zero- or microgravity i.e., the space gravity. The velocity of air through the nozzles of ADFS varies up to 8.542 m/s to simulate the flow of vomit through the flushing speed up to 8.542 m/s during interplanetary missions such as Mars exploration, the Moon exploration, and the space missions (Fig. 19a–c).

The different parameters (residuals) such as velocity while flushing in X, Y, and Z directions ($u = u(x, y, z, t)$; $v = v(x, y, z, t)$; and $w = w(x, y, z, t)$), as well as continuity are compared with respect to iterations; the accuracy of the solutions presented herewith are found reasonably good from the start point to the next check point as their difference is lower than $1e^{-3}$. Residuals are the imbalances of the parameters that vary with respect to time or residuals are the difference between the particular values calculated at each iteration. The results are fairly good in agreement as the curves are almost smooth and consistent throughout the boundary conditions. The system is thus proposed to function as per its sustained solutions during its application. The units such as velocity and pressure are expressed in meters per second (m/s), and pascal (Pa) in all three principal directions.

Computational fluid dynamics (CFD) has been applied in a variety of research disciplines. For numerical analysis, the CFD model's target space is split into a finite number of grids. As a result, obtaining correct findings necessitates the use of an ideal grid design. The grid independence test is commonly used to create the best grid possible. Due to the lack of a defined technique for the grid independence test, the majority of researchers rely on their own experience and knowledge. The optimum grid resolution grew as the characteristic length increased. The suggested method's applicability was tested using the grid convergence index (GCI). As a consequence, all of the optimal grid resolutions generated from the suggested approach were deemed the best. The grid independence test was used to determine the best grid size for the current investigation. The influence of five different grid sizes (300×20 , 500×30 , 600×40 , 900×50 , and 1000×60) on the Nusselt number computed at a distance of 270 mm from the tube entrance was investigated. Beyond the grid size of 600×40 , no substantial variation in Nusselt number has been discovered ($24,000$). As a result, all simulations in this study were run on a $24,000$ -grid size.

The main difference between the considered cases is different magnitudes of gravity that gives different

velocities of the waste matter as an output. As the velocity is inversely proportional to time, the greater the velocity, the lesser the time fluid spends to travel the distance. The $\kappa - \epsilon$ turbulence model options are (1) mixture turbulence model (the default), (2) dispersed turbulence model, and (3) turbulence model for each phase. The explanations of each technique provided here are based on the conventional $\kappa - \epsilon$ model. Because the multiphase changes to the RNG and realisable $\kappa - \epsilon$ models are comparable, they are not discussed in detail. The default multiphase turbulence model is the mixed turbulence model. It is the initial extension of the single-phase $\kappa - \epsilon$ model, and it is used when phases split, in stratified (or nearly stratified) multiphase flows, and when the density ratio between phases is close to one. In many instances, capturing essential characteristics of the turbulent flow with mixture properties and mixture velocities is adequate. Mesh elements allow governing equations to be solved on predictably shaped and mathematically defined volumes. Typically, the equations solved on these meshes are partial differential equations. Due to the iterative nature of these calculations, obtaining a solution to these equations is not practical by hand, and so computational methods such as computational fluid dynamics (CFD) are employed.

In case of seat, initial conditions such as for air and fecal matter include air inlet velocity (8 m/s), air inlet pressure ($2 \times 10^5 \text{ pa}$) and fecal matter inlet velocity (0.04 m/s) are considered. In case of funnel, initial conditions such as for air and urine include air inlet velocity (8 m/s), air inlet pressure ($2 \times 10^5 \text{ pa}$), and urine inlet velocity (0.04 m/s) are considered. In case of basin, initial conditions such as for air and vomit includes air inlet velocity (8 m/s), air inlet pressure ($2 \times 10^5 \text{ pa}$), vomit inlet velocity (0.06 m/s) are considered. A brief comparison is made between the previously proposed space toilets and the present self-sustainable space toilet for interplanetary missions such as Mars, and the Moon as well as the space as listed in Table 2.

14.3 Compressor evaluation

The displacement volume can be evaluated using Eq. (11) based on the product of the area of cylinder and the stroke length [30].

$$\text{Volume displacement } (V_d) = AL \quad (11)$$

In the above Eq. (11), the parameters such as area, A, and stroke length, L, are evaluated as 0.013066 m^2 , and 0.055 m , respectively.

The volume displaced by the bellows can be expressed using Eq. (12) based on the ratio of chamber volume to the volume occupied by the bellows.

Table 2 A brief comparison with other available ISS toilets proposed so far

Proposed toilets	Taylor [1]	Son et al. [29]	Sakhare et al. [present]
<i>Parameters</i>			
Microgravity (the space/ interplanetary mission)	International space station	International space station	The space/interplanetary mission
Approaches (CFD model and other numerical analysis)	–	CFD-Toilet system air flow analysis	The CFD model for multiphase flows
UWMS	Yes	Yes	Yes
Waste and hygiene compartment	Yes	Yes	Yes
Capacity of the waste container (astronauts uses and working days)	–	20 L (ISS) of fecal matter	17.671 L of fecal matter (02 astronauts for 14 days)
Bellow pump or, common cabin air assembly fan	–	Common cabin air assembly fan	Bellow pump
Urine storage/ urine processing unit	Urine processing unit	Urine processing unit	Urine storage as well as urine processing unit
Vomitation	No	No	Yes
Defecation as well as menstruation	Yes	Yes	Yes
Germ inhibition	No	No	Yes
Disposable/reusable plastic bags for waste storage	–	Disposable	Reusable
Male/female astronauts	Unisex	Unisex with separate funnel for urination	Unisex with a common funnel for urination
Faecal waste management	Yes	Faecal wastes are burnt/thrown in the space	Faecal wastes are used as compost to support living systems of planets such as Mars

$$\text{Volume displacement by bellows} = \frac{V_d}{1.46} \quad (12)$$

The mass of air per cycle can be expressed using Eq. (13) using the gas constant relationship [30].

$$\text{Mass of air}(m_a)\text{per cycle} = \frac{P_1 V_1}{RT_1} \quad (13)$$

where the parameters such as inlet pressure, P_1 , and inlet temperature, T_1 , are considered as 100 Kpa, i.e., 1 bar, and 24 °C, i.e., 297 Kelvin. The gas constant, R is taken as 0.287 kJ/kgK.

The mass flow rate of the air can be calculated using Eq. (14) [30].

$$\text{Mass of air}(\dot{m}_a)\text{per minute} = m_a N \quad (14)$$

In the above Eq. (14), the rotational speed, N , is 200 RPM.

The temperature of the air (T_2) leaving the compressor can be calculated using Eq. (15) based on the polytropic process relationship [30].

$$\frac{T_2}{T_1} = \left[\frac{P_2}{P_1} \right]^{\left(\frac{n-1}{n} \right)} \quad (15)$$

In the above Eq. (15), the outlet pressure, P_2 , is 200 Kpa, i.e., 2 bar.

The mechanical work required to compress the air can be calculated using Eq. (16) [30].

$$\text{Work input}(W_{in}) = \frac{\dot{m}_a R (T_2 - T_1)}{60} \left(\frac{n}{n-1} \right) \quad (16)$$

In the above Eq. (16), the parameter such as work input, W_{in} is evaluated as 185 W.

The electrical power input to the motor can be calculated using Eq. (17) after dividing the mechanical work by the electrical efficiency.

$$\text{Electric power}(P_{in}) = \frac{W_{in}}{\eta_e} \quad (17)$$

In the above Eq. (17), the electrical efficiency is considered as 0.93.

The overall electrical power, P_{in} , is evaluated as 199 W.

15 Conclusions

The proposed unisex and self-sustainable waste collection system (WCS) is designed for maximum comfort and flexibility to the crew members in terms of its

Table 3 Bill of materials: parts used in the numerical simulation of self-sustainable space toilets for any gravitational condition and inter-planetary missions

Level	Quantity (QTY.)	Part name	Material selection as per the requirement of NASA's lunar loo challenge	Density (kg/m ³)	Young's modulus (MPa)	Poisson's ratio
1	1	Seat	Polycarbonate (PC) (strong and tough, high impact resistance, elevated temperature application)	1190	2200	0.36
2	1	Urine funnel	Polycarbonate (PC) (strong and tough, high impact resistance, elevated temperature application)	1190	2200	0.36
3	1	Basin	Polycarbonate (PC) (strong and tough, high impact resistance, elevated temperature application)	1190	2200	0.36
4	2	Bellows	Ethylene propylene diene monomer (EPDM) (extraordinary resistance to heat, electric insulator, and fire proof application)	8600	6.73	0.48
5	1	Urine storage	Aluminium alloy 7075 (light weight and anticorrosive features; strength at low temperature)	2800	717,000	0.33
6	1	Urine storage cap	Aluminium alloy 7075 (light weight and anticorrosive features; strength at low temperature)	2800	717,000	0.33
7	2	Urine filter	Aquaporin inside® hollow fiber forward osmosis Membrane (FO)	—	—	—
8	1	Faecal storage cap	Aluminium alloy 7075 (light weight and anticorrosive features; strength at low temperature)	2800	717,000	0.33
9	1	Faecal storage casing	Aluminium alloy 7075 (light weight and anticorrosive features; strength at low temperature)	2800	717,000	0.33
10	1	Fecal waste storage	Aluminium alloy 7075 (light weight and anticorrosive features; strength at low temperature)	2800	717,000	0.33
11	1	Reusable plastic bag	High density polyethylene (HDPE) (high impact resistance and melting point)	9410	1500	0.46
12	1	Casing of pump	Aluminium alloy 7075 (light weight and anticorrosive features; strength at low temperature)	2800	717,000	0.33
13	5	Non return valve	SMC pneumatic bulkhead tube-to-tube adapter straight push in 4 mm to push in 4 mm	—	—	—
14	7	Solenoid valve	RS PRO solenoid valve, 2 port, NC, 24 V DC	—	—	—
15	1	Support frame	Aluminium alloy 7075 (light weight and anticorrosive features; strength at low temperature)	2800	717,000	0.33
16	8	Flexible hose pipes	Composites (Stainless Steel (SS) corrugated, teflon, rubber, copper, G.I., P.V.C, nylon)	—	—	—
17	19	Elbow [31]	Titanium, stainless steel, or teflon wrapped in metal mesh (compact, lightweight, corrosion-resistant, leak-resistant, microbe-resistant, and highly dependable)	8000	190,000	0.265
18	8	T-joint [31]	Titanium, stainless steel, or teflon wrapped in metal mesh (compact, lightweight, corrosion-resistant, leak-resistant, microbe-resistant, and highly dependable)	8000	190,000	0.265
19	12	Pipe [31]	Titanium, stainless steel, or teflon wrapped in metal mesh (compact, lightweight, corrosion-resistant, leak-resistant, microbe-resistant, and highly dependable)	8000	190,000	0.265

maintenance and cleanliness during its operation in different gravitational conditions such as (a) Mars (3.721 m/s²), (b) the Moon (1.62 m/s²), (c) the zero- or microgravity i.e., the space gravity. The crew member just has to sit, turn on the system, and do the job, and after he/she is done, it needs to turn off the system. The designed WCS keeps itself clean (hydrophobic coating) and preserves

waste for a given time, thus fulfilling its objectives such as it (a) supports the water recovery and its management (WRM) system, (b) converts the semisolid wastes into reusable compost to support living systems, and (c) supports the bioregenerative life support system; and thereby reducing the space junk.

The present investigation is focused on the design of compact and lightweight WCS for interplanetary missions such as Mars, and the Moon as well as the space with the required features of NASA's lunar loo challenge (released date: 25th June, 2020) [10]. The newly designed unisex and self-sustainable space toilet fulfils its objective of intimacy and warmth for the astronauts as it is equipped with all essential features such as (a) the basin (30 cm wide and 30 cm long, having a depth of 5 cm) for vomit collection (the area of the basin around 678 cm²), (b) the rotating waste storage containing reusable plastic bag based on the mechanism of artificial gravity, and (c) the noiseless bellow (silicon rubber material) pump for its smooth operation at the low-temperature, i.e., -270°C powering the air flow flushing system (AFFS). The newly designed WCS is proposed for simultaneous urination and defecation, and to collect urine, faeces, vomit, diarrhoea, menses for a required journey of 14 days (two uses per day for defecation, and six uses per day for urination) [10]. The funnel, the seat, and the basin are provided with a set of nozzles around their periphery to flush the matter with high-velocity air, which directs the waste towards the storage (Fig. 6). The present self-sustainable WCS does not use water at all, and thus, reduces weight and saves the prestigious water just for the essential needs.

The computational fluid dynamics approach is used to simulate the flow of air through the nozzle provided with (a) the seat (average mesh element sizing, 10 mm; the nozzles declined at an angle of 45° with respect to the XY plane to drift the air flow with a velocity of 8 m/s), (b) the urine funnel (average mesh element sizing, 32 mm; nozzles declined at an angle of 55° with respect to the XY plane to drift the air flow with a velocity of 8 m/s), and (c) the basin (average mesh element sizing, 10 mm; nozzles declined at an angle of 20° with respect to the XY plane to drift the air flow with a velocity of 8 m/s) for air flow flushing system (AFFS). For the seat, funnel, and basin, with an increase in the velocity of air through the nozzles, the flushing speed of fecal matter, urine, and vomit increase up to 9.608, 10.03, and 8.542 m/s, respectively in different gravitational conditions such as (a) Mars (3.721 m/s^2), (b) the Moon (1.62 m/s^2). For the seat, funnel, and basin, with an increase in the velocity of air through the nozzles, the flushing speed of fecal matter, urine, and vomit increase up to 15.06, 13.6, and 8.542 m/s, respectively in the microgravity condition. The different parameters (residuals) such as air flushing velocity in X, Y, and Z directions ($u = u(x, y, z, t)$; $v = v(x, y, z, t)$; and $w = w(x, y, z, t)$), as well as continuity are plotted with respect to iterations; the accuracy of the solutions presented herewith are found reasonably good throughout the operation as their difference does not exceed 1e^{-3} . The efficacy of the present investigation is established as well as the curves

are almost smooth and consistent throughout the boundary conditions.

The self-sustainability of the proposed space toilet is discussed for interplanetary missions such as Mars, and the Moon as well as the space as it promotes the in situ resource management (ISRM) program, and thus, save room in the spacecraft and reduce its weight. It could be easily integrated with the current water recovery and management system (WRM) is used on the ISS for the treatment of (a) waste water and (b) urine. The composting chamber integrated with the fecal waste storage could be used to convert the waste matter into compost within 4–5 weeks at the rate of 6–7% (weight percentage) in the space toilet. The proposed space toilet promotes the Project MELiSSA for the bioregenerative life support system (BLSS) [24]. The biomass processed in the chamber is sufficient to provide foods (protein 61%, carbohydrates 13.4%, etc.) for the crew members. In addition to that, the assessment of the required electrical energy derived from the solar energy (harnessed using efficient solar photovoltaic (PV) modules) is conceptualized for the effective functioning of the present self-sustainable WCS. The overall electrical power required to power the AFFS's pump is evaluated as 199 W based on the analytical approach involving polytropic process algorithms.

Availability of data and materials The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

The parts used in the design and numerical evaluation of self-sustainable space toilets for any gravitational condition and interplanetary missions (as per NASA's lunar loo challenge) are listed in Table 3 for its optimum performance.

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