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An efficient approach for spaceflight solid waste treatment: Co-disposal with hazardous medicine by hydrothermal oxidation process

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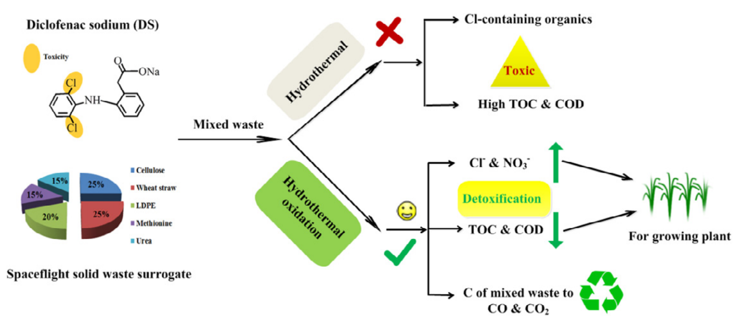
HIGHLIGHTS

- SSW containing waste DS drug can be harmlessly disposed in the HTO process.
- The optimal dechloridation efficiency were obtained over 95%.
- The liquid product displayed the potential for plants growing in the ECLSS.
- A large amount of CO_2 showed the superb oxidation level of the HTO process.

GRAPHICAL ABSTRACT



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ABSTRACT

Spaceflight solid waste (SSW) is different from terrestrial municipal solid waste since it contains quite amount of medicines needing co-disposal sometimes. Harmless co-disposal of the hazardous drug discarded into SSW is extremely important for safe operation of the Environmental Control and Life Support System (ECLSS) during long-term space missions. In this work, hydrothermal oxidation (HTO) process was proposed for detoxification and mineralization treatment of the blend waste comprising of SSW and waste drugs (diclofenac sodium, DS). The results showed that a large number of toxic chlorinated organics were detected in the hydrothermal process without oxidant. On the contrary, in the presence of oxidant (H_2O_2), an efficient dechlorination and detoxification level was achieved above 300 °C. The optimal conditions including temperature, time and H_2O_2/waste (H/S) ratio were 300 °C, 30 min and 30 mL/g, respectively. The dechloridation efficiency and carbon conversion efficiency under the optimal conditions were over 95% and 77%, respectively. Furthermore, a suitable concentration of nitrate, TOC and COD were also obtained under the optimal conditions, implying that the by-products after the HTO process exhibited the potential for plant growing in the ECLSS. Compared with other oxidation techniques for waste disposal in space, HTO process exhibited significant technical advantages of disposing the blend waste containing waste medicines and SSW. Accordingly, HTO process was recommended as a promising, efficient and environment-friendly method to dispose spaceflight solid waste containing various types of hazardous matters during long-term space missions.

1. Introduction

In recent times, longer sojourns in space have become more and more common, and the number of plans for manned missions to Mars is steadily increasing [1]. During long-term space missions, it is extremely important to support astronauts' health, which is a restrictive factor for

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the successful achievement of space missions [2]. The negative physiological changes on astronauts' bodies due to the extreme environment of space require pharmacotherapy to treat different space diseases during future deep space exploration missions [3,4]. Unfortunately, recent studies have shown that the drugs may degrade more rapidly in space [5,6], and their degradation products are toxic [7], which could be harmful for astronauts' health and contaminate the Environmental Control and Life Support System (ECLSS). Therefore, these discarded drugs need to be properly disposed. Currently, waste medicines from the International Space Station are simply collected, and returned to the earth for disposal. However, for longer duration missions to Mars or other asteroid, the replacement of medicines is highly limited during long-term space missions, so waste medicines would generally be discarded into SSW [8]. Meanwhile, some drug molecules can migrate into SSW with astronauts' metabolites [9], which is the potential source of contaminants in the ECLSS. In actual, the SSW and waste medicines could not be collected separately for reducing astronauts' workload during long-term space missions. NASA' s technical handbook also mentioned that waste medicines produced in space missions should be harmlessly disposed [10]. SSW is different from terrestrial municipal solid waste, e.g., the amount of conventional solid waste produced on the earth is large, and waste drug molecules migrating into the garbage could be diluted. However, the amount of SSW is relatively small, and waste medicines migrating into SSW would account for a larger proportion resulting in higher environmental risk in the ECLSS. Therefore, there is a need to develop a reliable, safe and environment-friendly approach for co-treatment of SSW and waste medicines, aiming to control the contaminants in the ECLSS during long-term space missions.

Diclofenac sodium (DS) is a typical chlorine-containing non-steroidal anti-inflammatory drug, and it is also a commonly used drug during long-term space missions [11]. It is commonly used to cure the inflammatory diseases due to the weightlessness environment during long-term space missions, e.g., low back pain. Waste DS is recognized as a priority pollutant due to its adverse effect on human health and the environment [12]. Generally, chlorine-containing part of molecular structure leads to the toxicity of chlorinated pharmaceuticals [13]. In particular, the toxicity of chlorinated intermediates is higher than their parent compounds during the treatment process, and the occurrence of dechloridation of chlorinated organics can be considered as reduction of the toxicity [14]. Hence, the improvement of dechlorination process can effectively reduce the toxicity of the products, resulting in the detoxification treatment of SSW mixed with waste DS.

In recent years, hydrothermal oxidation (HTO) technique has been investigated as an environment-friendly method to solve environmental problems caused by hazardous wastes [14–16]. HTO has extraordinary properties (e.g., low viscosity, high mass transport coefficient, high diffusivity, and fast reaction rates etc.), which were widely used to decompose hazardous organics [17]. In the HTO process, hazardous organics can be decomposed into benign small molecules [18,19]. Meanwhile, HTO process is one of the several potential options for solid waste disposal during long-term space missions [20,21]. An ancillary advantage of HTO process is that any possible pathogens (e.g., biotoxins, bacteria or viruses) in solid waste are completely sterilized, which can solve the problem of unpleasant and toxic odors due to the microbial decomposition [22]. The organics can be converted to oxidative products in the HTO process, such as CO_2 and H_2O, which can be effectively utilized by other systems of ECLSS for resource recovery [23]. To the best of our knowledge, quite little work is found in literature concerning the harmless co-treatment of SSW and waste medicines during long-term space mission. HTO process has significant technical advantages to dispose the SSW containing discarded medicines for pollution control and simultaneously resource recycling.

In this work, HTO process was employed to harmlessly co-dispose waste medicines and SSW during long-term space missions. Dechloridation efficiency was adopted to assess the detoxification level of the co-treatment process. Chemical oxygen demand (COD) and total organic carbon (TOC) of the liquid products, concentrations of nitrate ion in the liquid products, and carbon conversion efficiency were also measured as indicators to comprehensively evaluate the oxidation level of the co-treatment process. These indicators in the hydrothermal process without oxidant were also analyzed. The effects of various parameters on various indicators in the HTO process were systematically investigated, and the comparison with other oxidation techniques for waste disposal during long-term space missions was discussed in detail.

Table 1
Composition of LFWS.

Ingredient	Function	Dry weight (wt %)
Cellulose	Waste paper	25
Wheat straw	Food scraps and inedible biomass	25
Low-density polyethylene (LDPE)	Plastic and plastic wrapping	20
Methionine	Feces	15
Urea	Biological waste	15

2. Experimental section

2.1. Materials

Diclofenac sodium (DS, $C_{14}H_{10}Cl_2NNaO_2$) was provided by Dongtai Pharm Co., Ltd. Henan, China. Hydrogen peroxide (H_2O_2, mass of 30%) and dichloromethane were chemical reagents from Sinopharm Chemical Reagent Co. Ltd. Beijing, China. LFWS developed by NASA's previous work [24] was employed to represent typical components of SSW during long-term space missions. As shown in Table 1, LFWS consisted of 25% cellulose, 25% wheat straw, 20% low density polyethylene (LDPE), 15% methionine, and 15% urea. The basic characterization of LFWS (e.g., proximate and elemental analysis, thermogravimetric analysis and Fourier transform infrared spectroscopy analysis) was conducted in our previous study [25]. Briefly, LFWS contained a high volatile matter, mainly consisted of carbon and oxygen, and also contained various functional groups.

2.2. Experimental procedure

At present, there are few opportunities to carry out experiments in the actual microgravity environment, and the cost of these experiments are very high. Researches concerned on spaceflight waste are all carried out on the earth, and the relevant results can provide fundamental data for its application in space [26]. Therefore, we conducted the experiments on the earth. Fig. 1 illustrates the experimental apparatus. The hydrothermal experiments were conducted in a 100 mL batch reactor made of Hastelloy-C276 alloy, which was designed to achieve the maximum temperature and pressure of 500 °C and 40 MPa, respectively. In all the experiments, the constant mass ratio of DS and LFWS were homogeneously mixed with the constant mass of deionized water. After sealing the reactor, high-purity argon was imported into the reactor to replace the air. As soon as temperature reached up to the setting value, the reactor was held for a specified time. Experimental temperature changed from 200 to 400 °C, and residence time changed from 0 to 90 min. Uncondensed gas was collected by a gas collecting bag for further analysis, and the total volume of collected gas was measured by a syringe with scale. Deionized water was used to remove the residual liquid product in the pipeline of the reactor. The liquid–solid mixture was separated by vacuum filtration. Solid product was not analyzed in detail due to its low yield. Organics in the liquid product were extracted using dichloromethane as extraction agent for subsequent analysis.