Converting gaseous pollutants toxic to plants and humans into environmentally friendly compounds in artificial ecosystems

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Abstract. The present study describes detection of potential gaseous pollutants that can produce a toxic effect on plants and humans in the system with wheat plants cultivated on solutions containing liquid products of mineralization of human waste and fish waste. These gaseous pollutants do not inhibit plant growth and development under the experimental conditions, but they may accumulate in closed ecosystems functioning for extended periods of time. Ways to convert gaseous pollutants into environmentally friendly compounds have been proposed.

1. Introduction

Partially closed ecological systems (CES) are indispensable for the practical application of space programs, as they are created as habitats for humans in long-duration space missions. Higher plants are proposed as a component generating air, water, and plant-based part of the diet for humans. Nutrients for plants can be derived from the processed human waste [1-3].

Researchers of the IBP SB RAS have developed a physicochemical method of human waste mineralization using hydrogen peroxide in alternating electromagnetic field [4]. If plants are to be grown on the media containing liquid mineralized human waste in a system with closed material loops, their tolerance to unfavorable environmental conditions may become an issue and should be carefully studied: the higher plant component will be responsible for producing oxygen and food for humans in the CES and, thus, must have high photosynthetic productivity. The gaseous composition of the air in the CES may be one of such unfavorable factors, as it may be affected by liquid mineralized human waste included in the mass transfer in the system. The purpose of this study was to detect possible gaseous pollutants toxic to plants and humans in the CES and analyze technological approaches to converting gaseous pollutants into environmentally friendly compounds.

2. Methods

Experiments were conducted in a 3-m^3 hermetically sealed plant growth chamber. Wheat (*Triticum aestivum* L., line 232 selected by G.M. Lisovsky) was grown hydroponically on expanded clay aggregate. Wheat plants were grown under a 16 hL/8 hD photoperiod for 84 d, from germination to maturity. Metal halide lamps DM3-3000 were used as the light source. Photosynthetically active radiation (PAR) intensity at the level of the leaves of the upper tier was 180 ±10 W/m^2. The air temperature in the chamber was 24 ± 1 °C in the daytime and 20 ± 1 °C in the nighttime, and relative humidity was 60–70 %. CO_2 concentration in the chamber was maintained between 400 and 2500 ppm

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except when the effects of elevated (5000 ppm) or reduced (130 ppm) CO_2 concentrations on the photosynthetic activity of the plants were studied. To prevent oxygen concentration from rising above 24%, the chamber was opened once a week to air it.

The wheat conveyor consisted of 6 age groups, with the interval of 14 days between sowings (one cycle). Plants were grown on nutrient solutions based on liquid products of mineralization of human waste and fish waste. The human waste mass to fish waste mass ratio was determined before co-mineralization of these wastes [3]. The animal protein requirement of a human is about 50 g/d, and protein content of 100 g fish is about 16 g. Thus, the daily amount of fish waste was determined as the mass of the waste corresponding to 312.5 g of the crucian carp flesh. After drying, this mass was about 50±2 g. The daily amount of the waste of one human is 150 g feces and 1.5 L urine. The waste was mineralized for several hours, until the complete decomposition of hydrogen peroxide occurred.

After the conveyor-grown wheat communities were established, 250 ml mineralized human waste and fish waste was added to the nutrient solution every day (Table 1). To maintain the necessary concentration of potassium in the nutrient solution, mobile ions were extracted from wheat straw by the water extraction method [1]. Each day, the same amount of the aqueous extract (250 ml) was added to the nutrient solution for irrigating the wheat community (table 1).

Table 1. Concentrations of mineral elements in mineralized waste, replenishing solutions, and wheat dry biomass (the error was no more than 10% of the measured value).

Sample	Ca	K	Mg	Na	P	S	N
Mineralized human waste and fish waste, mg/L	755	1071	150	1212	689	231	5720
Wheat straw extract, mg/L	350	1550	200	316	37	85	127
Daily requirements of wheat community, mg	159	533	79		105	63	502
500 ml of replenishing solution	276	655	88	382	181	79	550

3. Results and Discussion

The air was analyzed for nitrogen oxides (NO, NO_2), CH_4, NH_3, CO, and volatile organic compounds. Maximum allowable concentrations (MACs) of the low-molecular-weight gases for humans are listed in table 2.

Table 2. MACs of the low-molecular-weight gases in the plant growth chamber during cultivation of uneven-aged wheat plant community on the nutrient medium based on liquid products of mineralization of human waste and fish waste [6].

MAC mg/m^3	Maximum	Daily mean
NO	0.4	0.06
NO_2	0.2	0.04
CO	5	3
CH_4	300	
NH_3	0.2	0.04

No NO_2 or CO were detected in the air. Trace amounts of NH_3 were detected. NO and CH_4 concentrations for one cycle are shown in figures 1 and 2.

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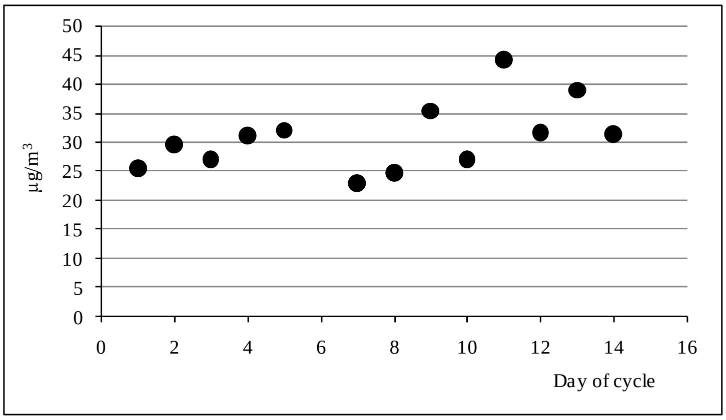

Figure 1. NO concentration in the air of the plant growth chamber during cultivation of uneven-aged wheat plant community on the nutrient medium based on liquid products of mineralization of human waste and fish waste.

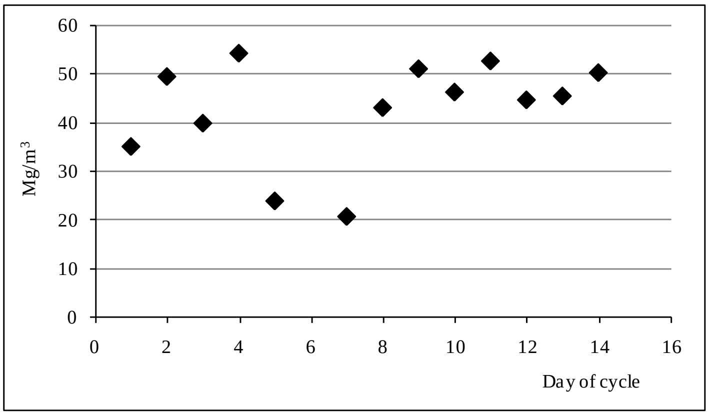

Figure 2. CH_4 concentration in the air of the plant growth chamber during cultivation of uneven-aged wheat plant community on the nutrient medium based on liquid products of mineralization of human waste and fish waste.

All measurements showed an NO concentration that was lower than the daily mean MAC by a factor of almost 2, except the measurement at Day 11, when NO concentration approached the daily mean MAC (figure 1, table 2). However, why NO was detected in the chamber that was aired weekly needs to be explained, and ways should be found to remove this compound from the air of the closed system in long-duration experiments.

CH_4 concentration in the chamber was no greater than 60 ppm, and that was considerably lower than the MAC for humans (figure 2, Table 2). As CH_4 concentration in the indoor air varies between 16 and 32 ppm, the presence of this gas in the air of the chamber should not cause any major concern.

Volatile organic compounds of a total concentration of 21.6 mg/L were detected in the air of the plant growth chamber (table 3). The major compounds were saturated and unsaturated hydrocarbons, alcohols, aldehydes, and benzene and phenolic compounds.

Table 3. Volatile organic compounds in the air of the plant growth chamber.

Volatile compounds	g/m^3
pentene	2.95
xylene	0.87
4-(methoxymethyl)phenol	0.57
1,3-dimethylbenzene	2.10
benzaldehyde	0.64
limonene	3.01
undecane	2.86
tridecane	1.48
tetradecane	7.38
Total	21.86

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The volatile organic compounds detected in the air of the chamber were converted into harmless substances using the method of oxidation on the platinum catalyst developed previously [7]. The temperature of the catalyst was increased to 850-900 °C, and the air was passed through the catalytic chamber at the velocity that enabled the contact of the air with the catalyst for at least 1 sec. Under these conditions, methane was completely oxidized (which could not be achieved at a lower temperature of the catalyst – 600-650 °C) to environmentally friendly compounds (CO_2 and H_2O), which were incorporated into the mass transfer. In addition to that, ammonia was oxidized to NO. NO was oxidized to NO_2, subsequently producing HNO_3 and, then, nitrogen fertilizers, using the method described elsewhere [8]. Thus, the compounds detected in the air can be maintained at trace concentrations, and such elements as C, H, O, and N can be returned to the mass transfer of the system as H_2O, CO_2, and HNO_3.

The state of the plants was evaluated based on CO_2 gas exchange and plant productivity, showing that gaseous compounds generated in the chamber during cultivation of wheat plants on solutions containing mineralized organic waste did not cause any unfavorable changes in the functional state of wheat plants (figures 3 and 4, table 4).

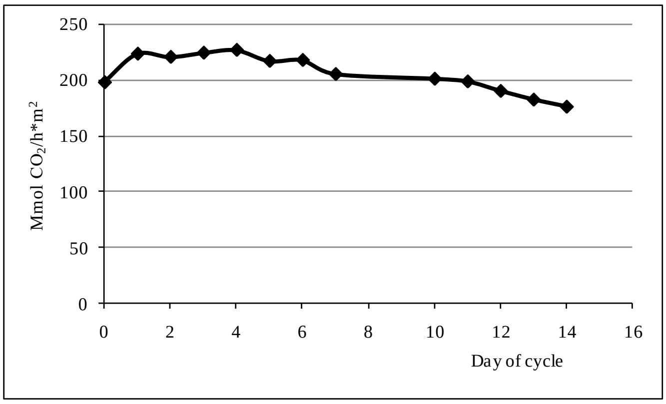

Figure 3. Net photosynthesis of the uneven-aged wheat plant community grown on the nutrient medium based on liquid products of mineralization of human waste and fish waste, at a CO_2 concentration of 1340 – 1390 ppm (average CO_2 concentration in the period of daylight).

Over the entire cycle, the net photosynthesis rate was approximately 200 mmol/h*m^2 at a CO_2 concentration of 1400 ppm (Figure 3). At the same time, the plateau of CO_2 saturation of the plant community was rather high (Figure 4), suggesting that no limiting factors other than CO_2 concentration were present under the light and temperature conditions used in the experiment. The nighttime respiration rate during the cycle was 79 - 88 mmol CO_2/h*m^2, amounting to about 40% of the average net photosynthesis. Thus, the daily net photosynthesis was 2536 mmol CO_2/m^2, enabling effective increase in plant biomass.

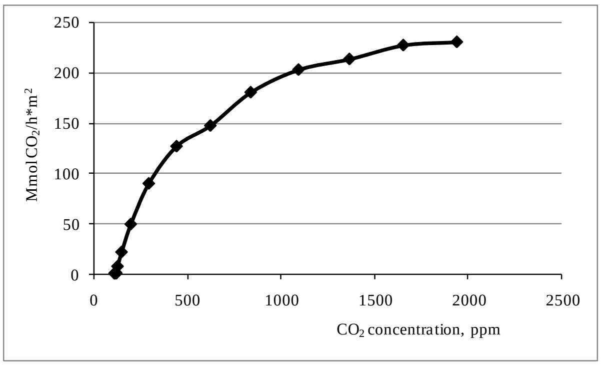

Figure 4. CO_2 dependence of the net photosynthesis rate of the uneven-aged wheat plant community grown on the nutrient medium based on liquid products of mineralization of human waste and fish waste.

Gaseous pollutants did not inhibit plant growth and development, producing no negative effects on the crop yield (table 4). The grain yield of the wheat plants grown in the "BIOS-3" biotechnical system was about 1.1 kg/m^2 (on a dry mass basis), and harvest index was 39–42 % [7]. In the present experiment, the grain yield was 73% greater and harvest index 4-7% higher than in the experiments in "BIOS-3".

Table 4. The structure of the crop yield of wheat plants grown on mineralized waste (the error was no more than 10% of the measured value).

Area of the growing surface, m^2	Number of plants	Number of ears	Total dry mass, g				Harvest index	Number of grains
			grains	1000 grains	straw and chaff	roots		
0.128	136	484	243	36	244	40	0.46	6774

4. Conclusion

During cultivation of wheat plants on solutions containing liquid products of mineralization of human waste, gaseous pollutants did not produce any toxic effects on plant growth and development and did not exceed their MACs for humans. Therefore, this approach to growing higher plants can be used in incompletely closed terrestrial artificial ecosystems (such as sustainable homes). However, in artificial ecosystems closed to a high degree and functioning for extended periods of time (for example, in space stations), pollutants may accumulate and their concentrations in the air may reach levels above their MACs. Then, gaseous pollutants should be converted into environmentally friendly compounds, and the present study proposes ecofriendly processes to achieve this.

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