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Designing the Future: An Intelligent System for Zero-Mile Food Production by Upcycling Wastewater †

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Abstract: The project deals with the environmental problem of water consumption. The aim of this work is to experiment the recycling of dishwasher wastewater through its reuse in growing edible vegetables or ornamental plants; this can also accomplish the valorization of nutrients present in the wastewater. This new process allows to ensure washing functions coupled with vegetables production and to affect users' environmental awareness and habits, following a user-centered system design approach to understand the users and involve them actively in the system development. The presented work is also aimed to experiment a multidisciplinary approach in order to face environmental problems.

Keywords: dishwasher wastewater upcycling; plant growth; User Centered Design

1. Introduction

The concept of sustainable development and especially the component of environmental or ecological sustainability require awareness of the natural resources and the fragility of the environment, the impact of human activities and decisions on it.

One of increasing environmental problem is the consumption of water resources in household appliances. In this context, we propose a technological system to recycle dishwasher wastewater in the cultivation of edible and ornamental plants, to limit domestic water use, reducing the amount of wastewater released in the environment and valorizing nutrients present in wastewater, and to improve the indoor environmental conditions (air quality, temperature and humidity). Furthermore, the system will produce healthy and safe zero-mile food, beneficial to user behaviour and health awareness.

The research relies on an interdisciplinary approach, by combining experimental methodologies and User Centered Design (UCD) techniques [1]: characterization of wastewater, plant growth and functionality analysis, technical design of the remediation plant, product and user inquiry, participatory design for expert and user involvement in the system ideation and development.

2. Material and Methods

2.1. Dishwashing, Analyses of Wastewaters and Study of the Household Treatment System

A household dishwasher (Energy Class A) was used, setting the "eco" program as washing cycle: the amount of wastewater discharged is about 12 L per cycle. As cleaning product, an EU Ecolabel certified dishwasher tablets detergent was selected, while the rinse aid has been excluded.

Two wastewater (W1, W2) and one potable water (C) samples were analyzed for physical-chemical parameters, being pH, BOD5, COD, and ionic composition. Analyses were performed according to Standard Methods [2]. Wastewater samples were collected under the same dishwasher operating conditions, but different loads in term of food residuals.

2.2. Plant Growth and Plant Descriptor Analyses

40 lettuce plants (*Lactuca sativa* L.), grown in 2.5 L pots with peat-based substrate, were divided into 4 batches: plants irrigated with wastewater (W) or potable water (C), and plants treated with a mineral NPK fertilizer and irrigated with wastewater (W/F) or potable water (C/F). Experiments were carried out indoors under artificial lighting (TLED 26W Growing, Secret Jardin) at photoperiod L:D 16:8 h.

During the vegetative cycle, plants were watered at a rate of about 40 mL/day per plant. After 48 days, the lettuce was harvested, immediately weighed (wet weight), then oven-dried at 105 °C for 72 h and reweighed (dry weight). Furthermore, plant functionality has been evaluated by biochemical descriptors: in vivo determination of leaves chlorophyll content was performed using a CL-01 chlorophyll meter (Hansatech, King's Lynn, UK) and chlorophyll a fluorescence was measured on dark adapted leaves using a portable fluorimeter (Handy PEA, Hansatech, King's Lynn, UK). Nitrate concentration was measured by the salicylsulfuric acid method [3] and calculated referring to a KNO_3 standard calibration curve.

2.3. User Centered Design Approach

The design of the integrated system for zero-mile food production by upcycling wastewater is based on a User Centered Design (UCD) approach. This methodology is developed on a multi-step process, that starts from the analysis of the users' behavior and continues with their involvement in the design practice. The UCD approach has been implemented according to these phases: benchmarking analysis of domestic innovative systems for indoor plant cultivation; secondary data analysis; focus group with consumers and stakeholders.

3. Results

3.1. Wastewater Characteristics and the Water Treatment System

Analytical results show a significant difference in the ionic composition between the two wastewater samples, as well as with the potable water sample. W1 and W2 samples were characterized by a high pH value (W1 = 9.3; W2 = 9.6; C = 6.9) and about 50 and 27 times higher concentrations of sodium (Na^+) ion compared to those measured in C sample (34 mg/L). The Na^+ increase leads to an increase in salinity (indirectly evaluated by electrical conductivity) and it can be ascribed to both the presence of Na_2CO_3 in the detergent and the ion exchange process which takes place in the water softener inside the dishwasher. Organic composition of W1 and W2 samples is largely derived from food residues and therefore it is highly variable. W2 sample presents a higher organic content in term of both COD (W1 = 730 mg/L; W2 = 2600 mg/L) and BOD5 (W1 = 210 mg/L; W2 = 1500 mg/L).

3.2. Plant Growth

The production and the quality of lettuce (*Lactuca sativa* L.) irrigated with wastewater or potable water did not show significant differences neither in wet and dry weight (*t* test, n.s.), nor in chlorophyll content ($p < 0.05$); the dry weights clearly show that the wastewater irrigation allows even a slightly higher growth than potable water and the use of wastewater (W) determined the highest accumulation of chlorophyll in leaves. Furthermore, leaf functionality was higher in plants irrigated with wastewater, as well as photochemical efficiency of PS II; the measure of the quantum maximum efficiency of PSII (Fv/Fm ratio) changed among different batches, ranging from 0.79 to 0.84: the highest index value was found in W, while it was significantly lower in fertilized batches irrigated with potable water (C/F). Lastly, nitrate content was lower in plants irrigated with wastewater (W ≅ 2900 mg/kg FW; W/F ≅ 2600 mg/kg FW) than with fertilizers, and the highest value was found in C/F (around 4000 mg/kg FW).

3.3. Benchmark, Consumers' Habits and Preferences

Benchmark analysis highlighted that just two companies proposed to connect kitchen's water consumption with plant cultivation by using a really integrated approach, but none of them considered wastewater recycling.

Regarding domestic products for growing indoor plants, the green wall systems show an interesting project's layout in terms of display and settings, responding to the needs of light and water, necessary for plant growth. Technological factors (such as integrated sensors and data processing systems) play an important role in these product systems, since they support the users in the growth and vegetative maintenance of plants.

The consumer's attitude towards diet is characterized nowadays by a kind of food polytheism [3]: therefore, the identification of a well-defined target for the eco-kitchen and the home cultivation of edible plants is unlikely. Accordingly, interviewees and focus-group participants confessed struggling with enacting sustainable behaviors in everyday life, but showed some concerns regarding the eco-kitchen, particularly related to the functional issues like space involved, costs, compatibility with clean home conditions, rather than with health issues.

4. Discussion

In this study, the reuse of dishwasher wastewater has been successfully obtained by growing lettuce plants: no statistically significant differences were found between wet and dry weights of plants irrigated with control potable water or wastewater. The good plant growth was obtained in spite of the wastewater characteristics, which could affect the feasibility of plant irrigation (salinity) or the stable development of the biological process. In fact, although it is known that plant growth reduced under salt-stress conditions in many vegetable species [5], the research findings can be explained by the moderate salt tolerance of lettuce plants [6]. Furthermore, as the 'Shelford tolerance law' states, plant growth is optimal within a nutrient concentration range [7]: the results of dry weight confirmed that the wastewater irrigation ensures even a slightly higher growth than potable water (even when plants were fertilized), thanks to the amount of organic matter and nutrients. According to the growth data, the physiological descriptors showed that wastewater plants batches were not stressed and had high light use efficiency; moreover, the use of wastewater did not affect the chlorophyll content of lettuce, ensuring a good leaf color, which is an important quality parameter that directly contributes to the visual appearance and consumer's attractiveness [8]. Nitrate content is also a relevant index, since high amount of this molecule in the diet can be harmful for human health [9]: in all samples, the levels were maintained below the limit imposed from the current EU regulation (CE No. 1258/20111). Furthermore, due to the use of the eco-labeled detergent, the composition of wastewater does not contain toxic components.

On that basis a conceptual system can be defined and a product developed, considering all different aspects from the functional to the aesthetic ones. In prospect, the integration of the wastewater treatment system in kitchen furniture, in combination with the vertical garden solution,

can push a change in the design of indoor growing modules, as well as in user behaviors, while improving the domestic water use efficiency, giving the research a first application outcome.

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