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Environmental Valorization of Rice Waste as Adsorbent Material for the Removal of Nitrates from Water

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Abstract: An innovative water-treatment process consisting in reducing the nitrate concentration by using an active silica filter obtained from ashes produced during rice-straw thermal treatment has been developed by the LIFE LIBERNITRATE project. A life-cycle assessment (LCA) was carried out to evaluate the environmental impacts of this innovative process, from the production of ashes and extraction and activation of silica to the water treatment. These results were compared to the environmental impact derived from the use of bottled water, instead of tap water, where traditional water treatments (i.e., reverse osmosis) may not be available due to the high installation and operating costs. The comparison showed that the proposed innovative process could contribute to reducing the environmental impact in almost all analyzed impact categories (from 20% for photochemical oxidation to 90% for abiotic depletion) with respect to the use of bottled water. In addition, if conveniently optimized (for example reducing the amount of active silica used per day), the innovative process could further reduce the ecological footprint and be more eco-friendly than the use of bottled water and could be applied to treating water in small towns where reverse osmosis may not be installed. The LCA proved that the innovative process could contribute to reducing the environmental impact of water-treatment technologies resulting in lower environmental indicators with respect to the use of bottled water.

Keywords: nitrate removal; life-cycle assessment; waste valorization; rice straw



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1. Introduction

The production of paddy rice worldwide was estimated at nearly 757 million tons in 2020 according to the Food and Agriculture Organization of the United Nations database [1]. Europe produced a total of 4 million tons with Italy and Spain being the largest producers with 1.5 and 0.8 million tons, respectively. An estimation in the FAOSTAT database states that 15 and 8 million tons of N are present in the crops in Italy and Spain and the production of nitrous oxide (NO₂) from the decomposition of nitrogen in crops left in the field is equal to 0.3 and 0.15 kilotons (Italy and Spain, respectively). These elevated N quantities present in the production cycle represent an important environmental impact with 87% of groundwater in Europe containing excess nitrates [2] due to intensive farming and use of chemical fertilizers. The areas vulnerable to N contamination have increased, especially in Spain, as per the Nitrates Directive [3] within the Water Framework Directive [4].

In addition to water pollution, the rice harvest is responsible of large quantities of residues that need to be dealt with: rice straw (remaining in fields after harvest) and rice husk (after post-processing). Every kilogram of harvested paddy produces 1 kg of straw and 0.2 kg of husk [5]. They are mostly disposed of in landfills, or abandoned in fields, causing severe impacts on human health and the environment due to major die-off of fish and other aquatic fauna in deeper areas [6]. Incineration without control is being regulated, although different European moratoria permit uncontrolled burning since no viable solutions are being implemented.

As a sustainable alternative, the use of agricultural by-products as precursors of materials with high adsorptive capacities is being investigated [7]. Adsorption is considered among the best methods for the removal of water pollutants due to its ease of operation and the ability to remove different types of pollutants, providing a wider applicability in water quality control [8,9]. Rice waste has been successfully used for the removal of Pb (II), Hg [10], Cd (II) [11], and nitrate from rice hull, achieving a maximum absorption capacity of 1.21 mmol/g [12]. Moreover, the ashes of rice waste contain a high silica content that, after an activation step, can be used in the removal of inorganic and organic pollutants from aqueous solutions [13].

In this framework, the EU-funded project LIFE LIBERNITRATE [14] promotes the use of renewable residual sources (rice straw) to obtain new silica-based adsorbents for nitrate removal from wastewaters. The consortium of the project comprises three universities: (Università di València and Universitat Politècnica de València—Spain, Università di Genova—Italy), two public bodies (Consorci de la Ribera—coordinator and Diputació de València—Spain), a farmers' association (Unió de Llauradors I Ramaders—Spain), a water-treatment company (Aguas de Valencia—Spain), and an incubator (Stitching Incubator—The Netherlands). The experimental work was carried out in the Valencian municipality of Alginet (Spain), a vulnerable zone within the Nitrates Directive, where several wells are out of service as they do not meet the required quality standards for drinkable water. The nitrate concentration was found to be 48 ppm according to the last public study (2013), showing an increasing trend. The established maximum concentration of nitrates allowed cannot exceed 50 ppm and thus efficient techniques to recover existing wells guaranteeing good water quality become necessary in the selected area of study.

The methodology is based on the incineration of rice straw in an own-designed and constructed valorization system. Pellets of rice straw are burned in optimized conditions to produce a maximized quantity of ashes with high silica content [15]. They are then used to treat water polluted with nitrates, representing an optimal example of circular economy strategy [16]. In fact, this valorization strategy could lead to a social and economic positive impact as a waste such as rice straw, that is currently caused environmental problems, would be used to produce new value-added materials useful for other processes, in this case, water treatment.

In fact, this innovative process could be applied to treat water in small towns (i.e., 200 inhabitants) where the reverse osmosis technology may not be installed, avoiding the use of bottled water. The areas with the greatest potential are made up of municipalities with between 200 and 1000 inhabitants located in areas of Europe whose bodies of water show high nitrate contamination. In Catalonia, Spain, the Valencian Community, Aragon, Castilla La Mancha, Andalusia, and the Balearic Islands; in Lombardia, Italy, Veneto and Venice; and in Macedonia, Greece, Thessaly and Central Greece, along with Cyprus and Malta stand out. These are areas with significant barriers to accessing water due to excess nitrates and serious difficulties in the implementation of conventional infrastructures or technologies. For example, in the Valencian Community the problem of excess nitrates affects more than 200 municipalities (such as the previously stated town of Alginet) that together have more than two million inhabitants.

For this work, a life-cycle assessment (LCA) was carried out to evaluate the environmental impacts of this innovative process, from the production of ashes and extraction and activation of silica to the water treatment, and to compare the results with the environmental impact derived from the use of bottled water, instead of tap water, where traditional water treatments (i.e., reverse osmosis) may not be available due to the high installation and operating costs.

2. Methodology

LCA is an internationally standardized, structured, and comprehensive method for quantifying the resources consumed and relevant emissions, the related environmental and health impacts, and the resource depletion associated with any goods or services [17].

LCA considers the whole life-cycle, from the extraction of resources, through production, use, and recycling, up to the disposal of the remaining waste. LCA studies aim to avoid “shifting of burdens”, reducing the environmental impact at one point in the life cycle, while increasing it at another.

The present work was carried out following the ISO 14040 (standard on LCA) with four main stages: (i) goal and scope definition; (ii) inventory analysis; (iii) impact assessment; and (iv) interpretation of the results. The goal definition is the first step of any life-cycle assessment. It must be clear and must identify the objective and aims of the study, the intended applications, and the targeted audience. During this phase, the objective of the LCA study (the scope definition) is identified and defined in detail.

The life cycle inventory (LCI) aims to identify and quantify the environmental factors crossing the system boundaries: raw material and energy inputs into the system and emission outputs from the system.

The objective of the impact assessment is understanding and evaluating the magnitude and significance of the potential environmental impacts of the system.

Finally, the results must be interpreted.

2.1. Goal and Scope Definition

The main goal of the present study was to evaluate the environmental impacts caused by the innovative process developed within the EU-funded project LIFE-LIBERNITRATE (Figure 1) and compare them with current technologies, in this case the use of bottled water.

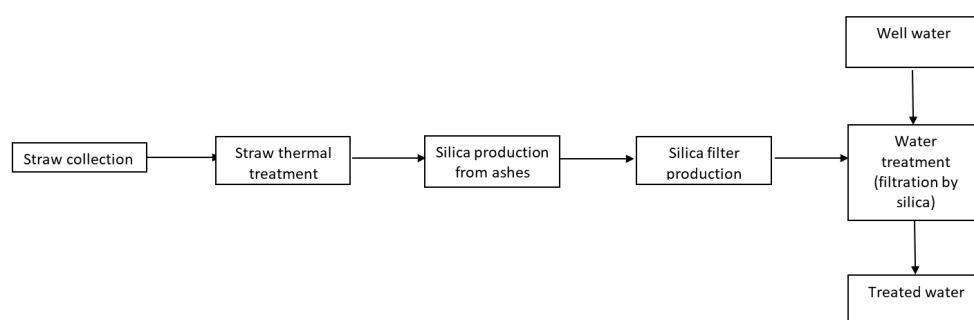


Figure 1. Scheme of innovative process developed within the EU-funded project LIFE-LIBERNITRATE.

The comparison allowed us to evaluate the potential environmental impact reduction and to verify in which situations the innovative process could be more sustainable with respect to other alternatives. With this aim, water treatment through active silica filtration was analyzed and compared with the use of bottled water.

System Boundaries and Functional Unit

The target of the project was the validation of active silica-bed prototypes for small municipalities (200 inhabitants) where the water consumption, per day, was estimated at about 26 m³, which defines the functional unit.

The LCA of water treatment using active silica included: rice-straw collection and transport; thermal treatment of rice straw obtaining energy and secondary raw material such as ashes; active silica production from ashes; water treatment by filtration with active silica; and disposal or recycling of waste. The relevant system boundaries are illustrated in Figure 2.

The system boundaries for bottled water are shown in Figure 3 and include: production of raw materials and energy for bottle production process; bottled water production process including the production of plastic bottles, caps, and packaging; bottled water transport; and disposal or recycling of waste.

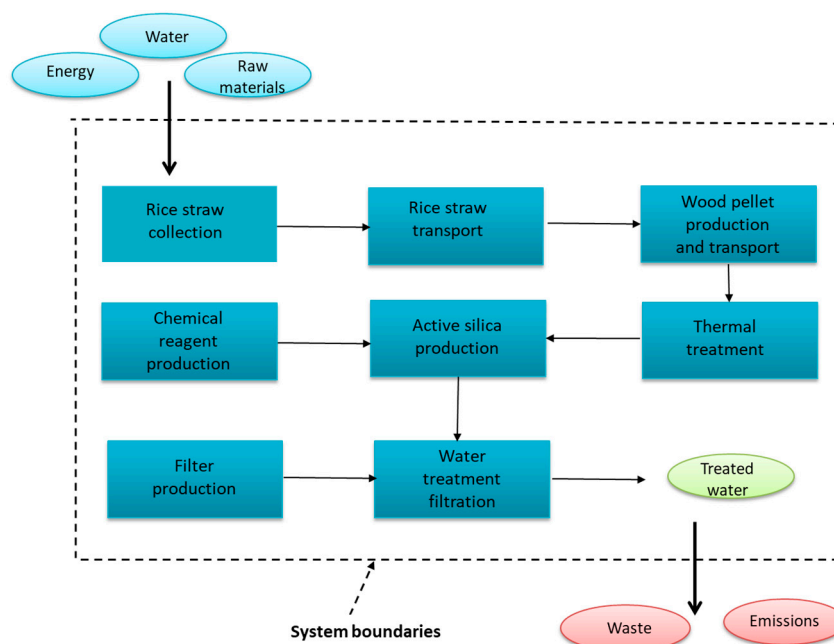


Figure 2. System boundaries of water-treatment process by active silica.

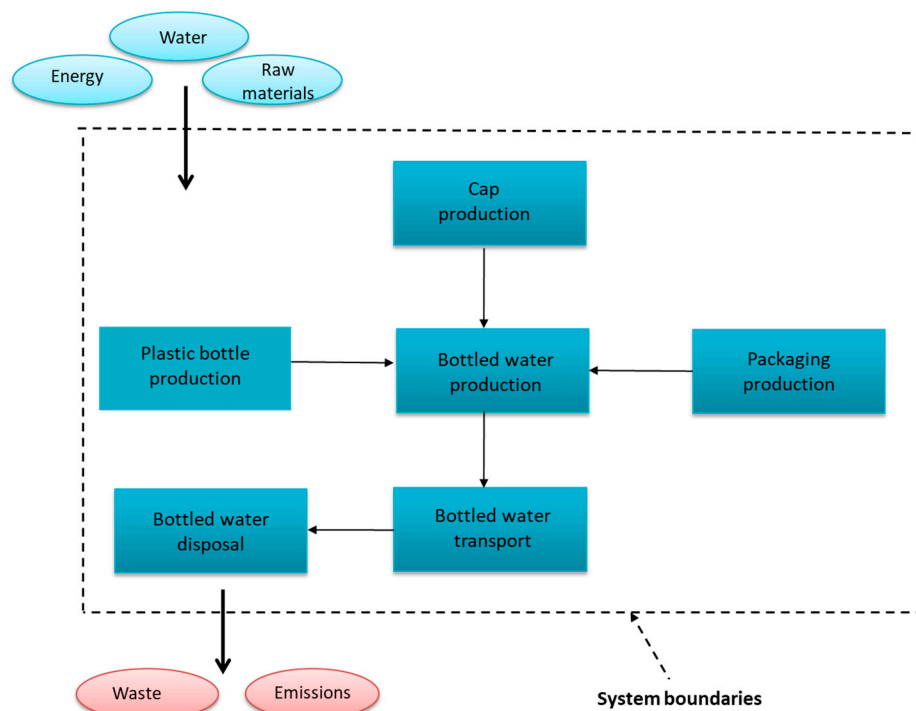


Figure 3. System boundaries of the use of bottled water.

2.2. Inventory Analysis

The LCI identifies and quantifies the inputs of raw materials and fuels into a system and the outputs of solid, liquid, and gaseous waste from the system. The inventory analysis was carried out using information from interviews with the project partners, experimental data from activities of the project, literature data, and information from Ecoinvent database (www.ecoinvent.org, accessed on 18 January 2022). The latter is a life-cycle inventory database that supports various types of sustainability assessments. It contains around 18,000 reliable life-cycle inventory datasets, covering a range of sectors: agriculture and animal husbandry; building and construction; chemicals and plastics;

energy, forestry, and wood; metals, textiles, transport, touristic accommodation, waste treatments, and recycling; and water supply, etc.

More details regarding the different analyzed systems are reported below.

2.2.1. Water Treatment by Active Silica

Data related to rice-straw collection were gathered from literature and interviews with the project partners.

For the rice-straw thermal treatment, data were mainly collected from the project experimental and simulation results. Some information (e.g., data of the entire wood pellet process to produce pellet from wood biomass) were obtained from the Ecoinvent database. Experimentally, pellets with mix of wood and rice straw (40% of wood/60% of rice straw, weight percentage) were fed to the incinerator.

Regarding the production of active silica and the water treatment by filtration, most data were obtained based on the project experimental results.

For water treatment, three commercial PWG (Pollet Water Group) vessels filled with 3 kg of active silica and Teflon were considered. The PWG vessel is made by a composite material (polyethylene and fibreglass) and can be reused and refilled for at least 10 years. In addition, Teflon can be reused at least for 1 year. Lastly, 3 kg of active silica can treat 3.4 m³ of water before disposal. Accordingly, the total amount of silica contained in the three vessels needs to be changed nearly three times a day to treat the 26 m³ of water (i.e., 27 kg of silica, in total, per day). In addition, another three filters need to be considered for use during the silica-activation phase. The inventory data of this system are shown in Table 1.

Table 1. Summary inventory data of innovative water-treatment process (¹ LIFE LIBERNITRATE). All data refer to the functional unit (26 m³ of water).

	Sub-System	Elements	Unit	Amount	Source
Input	Rice-straw collection	Diesel for engine to collect rice straw	kJ/kg	27.77	[18]
		Thermal treatment	Rice-straw transport Water Wood pellet Wood-pellet transport Electricity	kg × km kg kg kg × km kJ	670 × 50 20 450 450 × 50 128.950
	Silica production	Ashes Electricity NaOH H ₂ SO ₄ Ammonia 30% Ethanol APTES	kg kWh kg m ³ m ³ kg kg	108.42 1838 675 0.54 0.017 409 75.60	Project ¹ experimental results
	Water filtration	Plastic material (PE)	kg	0.038	Based on PWG vessel data sheet
		Glass fiber Teflon Silica	kg kg kg	0.038 0.18 27.00	Project ¹ experimental results
		Energy HCl for cleaning	kJ kg	398 0.55	
Output	Rice-straw collection	Uncollected rice straw	kg	170	Project ¹ partner interview

Table 1. Cont.

Sub-System	Elements	Unit	Amount	Source
Thermal treatment	CO ₂	kg	1920	Project ¹ simulation results
	H ₂ S	kg	1.45	
	Water	kg	640	
	SO ₂	kg	8.82 × 10 ⁻²	
Silica production	NaOH	kg	675	Project ¹ experimental results
	H ₂ SO ₄	m ³	0.54	
	Ammonia 30%	m ³	0.017	
	Ethanol	kg	409	
	APTES	kg	75.60	
Water filtration	Silica to recycling	kg	27.00	
	Plastic waste	kg	0.038	
	Teflon	kg	0.18	
	Glass fiber	kg	0.038	
	HCl	kg	0.55	

2.2.2. Use of Bottled Water

The inventory analysis of bottled water was made on the basis of literature data with most of the information adapted from a case study of an LCA of bottled water production [19]. In that case, data referred to a production of 6 litres of water whereas a quantity of 26 m³ of drinking water was defined in this study.

Bottles were supposed to be in polyethylene terephthalate (PET), one of the main materials used to produce water bottles. Two end-of-life scenarios were considered: disposal and recycling of PET bottles. Data related to bottle transport were identified based on the average distance between different Spanish bottled water production plants and Valencia (about 300 km).

The summary of the inventory data is reported in Table 2.

2.3. Impact Assessment

OpenLCA, an open-source software, and the CML 2 baseline method were used for the impact assessment. The analytical tool, developed in 2001 by the Center of Environmental Science of Leiden University, is in accordance with ISO 14040 standards.

The potential environmental impact evaluation of a process or system is carried out considering different impact categories that can be divided into three general groups in terms of impacting subjects: human health, natural environment, and resource depletion.

According to the CML 2 baseline method, the following impact categories were evaluated: *abiotic depletion and abiotic depletion (fossil fuel)*—the consumption of non-biological resources (fossil fuels, minerals, metals, etc.) and the value of the abiotic resource consumption of a substance (a measure of the scarcity of the substance); *eutrophication*—the increase in concentration of chemical nutrients in an ecosystem which leads to abnormal productivity and causes excessive plant growth such as algae in rivers leading to severe reductions in water quality and animal populations; *acidification*—acidic gases such as sulphur dioxide (SO₂) react with water in the atmosphere to form “acid rain”, a process known as acid deposition which causes ecosystem impairment to varying degrees, depending upon the nature of the landscape ecosystems; *global warming*—the rise in global temperature due to the greenhouse effect caused by the release of gases such carbon dioxide (CO₂) by human activity; *ecotoxicity*—environmental toxicity is measured as three separate impact categories which examine freshwater, marine and land; the emission of some substances, such as heavy metals, can have impacts on the ecosystem; *human toxicity*—the human toxicity potential is a calculated index that reflects the potential harm of a chemical compound released into the environment, and is based on the inherent toxicity of the compound and

its potential dose; *ozone layer depletion*—gases such as chlorofluorocarbons (CFCs) cause damage to stratospheric ozone or the “ozone layer” reducing the ability of stratospheric ozone to prevent ultraviolet (UV) light entering the earth’s atmosphere, increasing the amount of carcinogenic UVB light reaching the earth’s surface; and *photochemical oxidation*—ozone is toxic to humans at ground-level and is formed by the reaction of volatile organic compounds and nitrogen oxides in the presence of heat and sunlight [20].

Table 2. Summary inventory data of bottled water. All data are referred to the functional unit: 26 m³ of water.

	Elements	Unit	Amount		Source
			Waste Recycled	Waste Disposal	
Input	PET	kg	1257	1257	Adjustment from [19] and Ecoinvent database
	Plastic packaging film	kg	83	83	
	LPDE for label	kg	71	71	
	Polypropylene for cups	kg	98	98	
	Cardboard for packaging	kg	271	271	
	Water	kg	2170	2170	
	Electricity	kJ	234,000	234,000	
	Bottle transport	kg × km	27,000 × 300	27,000 × 300	Hypothesis of authors
Output	Mix plastic waste in landfill	kg	251	1509	Adjustment from [19] and Ecoinvent database
	Paperboard waste in landfill	kg		271	
	Plastic waste to recycling	kg	1257		
	Paperboard to recycling	kg	271		

3. Results and Discussion

To compare the different analyzed processes, the environmental impacts associated with them were calculated and split into the different categories listed above.

The results obtained are reported in Table 3.

Table 3. Potential environmental impacts of different water treatments.

Indicator	Unit	Innovative Process	Bottled Water (Recycling)	Bottled Water (Disposal)
Abiotic depletion	kg Sb eq	0.03	0.48	0.48
Abiotic depletion (fossil fuels)	MJ	3.80×10^5	1.20×10^6	1.25×10^6
Acidification	kg SO ₂ eq	14.62	19.75	21.23
Eutrophication	kg PO ₄ ³⁻ eq	5.21	6.43	13.19
Fresh water aquatic ecotoxicity	kg 1.4-DB eq	1.71×10^{-3}	2.27×10^{-3}	4.93×10^{-3}
Global warming (GWP100a)	kg CO ₂ eq	2.24×10^{-3}	5.78×10^{-3}	8.20×10^{-3}
Human toxicity	kg 1.4-DB eq	1.68×10^{-3}	3.38×10^{-3}	4.83×10^{-3}
Marine aquatic ecotoxicity	kg 1.4-DB eq	3.53×10^{-6}	5.41×10^{-6}	8.24×10^{-6}
Ozone layer depletion (ODP)	kg CFC-11 eq	1.26×10^{-3}	0.01	0.01
Photochemical oxidation	kg C ₂ H ₄ eq	1.10	1.23	1.42
Terrestrial ecotoxicity	kg 1.4-DB eq	9.30	7.53	11.23

With the aim of more easily comparing the different processes, relative results were analyzed.

In Figure 4, the chart shows each relative indicator where the maximum result is set to 100% and the other cases are displayed in relation to this result.

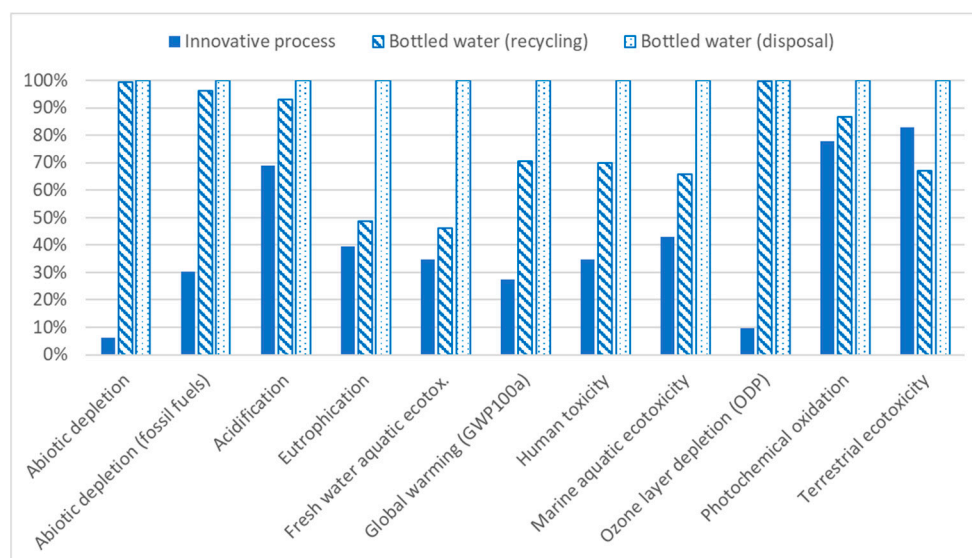


Figure 4. Potential environmental impact comparison between different water treatments: innovative process, use of bottled water with bottle recycling, and bottle disposal.

The innovative process showed a lower impact for nearly all analyzed categories with respect to the use of bottled water, specially when bottles are not recycled.

For abiotic depletion and ozone layer depletion categories, the reduction in the impact was 90% (from 0.48 to 0.03 kg Sb_{eq} and from 0.01 to 1.26×10^{-3} kg CFC-11_{eq}, respectively), whereas for acidification and photochemical oxidation the reduction was between 20 and 30% lower (from 21.23 to 14.62 kg SO_{2eq} and from 1.42 to 1.10 kg C₂H_{4eq}, respectively) with respect to the use of bottled water (without recycling) and in the range 10–20% (from 19.75 to 14.62 kg SO_{2eq} and from 1.23 to 1.10 kg C₂H_{4eq}, respectively) if bottles were recycled.

The most impacting stage of the innovative process is the production of silica from the ashes of rice straw. It is highly affected by the chemical reagents used such as sulfuric acid, ethanol, ammonia, and sodium hydroxide. These compounds generate significant impacts in the following categories: acidification, eutrophication, and photochemical oxidation.

The high level of the terrestrial ecotoxicity of the innovative process is due to both the chemical compounds previously described and to the energetic consumption and thus, to the related electrical energy for their production.

Some qualitative comparisons with other works can be made for each individual step. The higher potential environmental impact of bottled mineral water with respect to tap water from conventional drinking water treatments is reported in [21].

Different works [18,22,23] state that hindering the deleterious effects from burning rice straw in situ in the field and valorizing its use as fuel, fertilizer, or secondary raw material is important from the environmental point of view, which is in line with this work where rice straw was used to produce both energy and raw materials.

In addition, the results of an LCA study carried out to evaluate different advanced techniques for processing the surplus of rice straw (i.e., incineration, gasification, anaerobic digestion, fermentation, and integrated operation of fermentation and anaerobic digestion) showed that controlled thermal conversion (similar to this innovative process) had a high impact on the reduction of the overall environmental impact derived from rice waste [24].

It is important to consider that the scales of the two compared processes in this LCA study were different: data referring to the innovative process (thermal treatment of rice straw and active silica filtration system) were taken from experimental processes at laboratory-scale whereas data regarding bottled-water production resulted from consolidated and well-established industrial processes. In addition, further improvements to the lab-scale unit could be applied when scaled-up: i.e., heat recovery for pre-treatment in the thermal treatment to reduce the energy consumption or recovery and reuse of chemical

compounds in the active silica preparation before disposal to reduce waste production. In addition, the preliminary optimization of the active silica filtration system highlighted that the reuse of silica can be done at least up to 13 times, obtaining similar results for nitrate reduction, thus optimizing and making more efficient the scaled-up system with a decrease in the quantity of active silica used, per day, to treat 26 m³ of water. In more practical terms, discussions with the technical staff of the treatment plant concluded that the reduction of the time in the changeover of active silica could ease the maintenance of the filtration system and reduce costs due to the lowered quantity of active silica required. In this sense, if active silica was not replaced for a week (9.0 kg) the quantity could be reduced by roughly 95% per day (from 27.0 to 1.3 kg).

By reducing the quantity of silica used, the environmental impact was reduced significantly (around 95%) in all categories, except for ozone layer depletion for which the reduction was lower, roughly 40% (Table 4). This latter category is highly influenced by other processes such as Teflon production, whose quantity does not change from one scenario to the other as it is a filter compound, although it does not have to be replaced as often as the silica.

Table 4. Potential environmental impacts of innovative process vs. silica amount.

Indicator	Unit	Innovative Process—Higher Silica Amount	Innovative Process—Lower Silica Amount
Abiotic depletion	kg Sb eq	2.95×10^{-2}	1.47×10^{-3}
Abiotic depletion (fossil fuels)	MJ	3.80×10^5	1.86×10^3
Acidification	kg SO ₂ eq	14.62	7.16×10^{-1}
Eutrophication	kg PO ₄ ³⁻ eq	5.21	2.54×10^{-1}
Fresh water aquatic ecotoxicity	kg 1.4-DB eq	1.71×10^{-3}	8.42
Global warming (GWP100a)	kg CO ₂ eq	2.24×10^{-3}	1.29×10^2
Human toxicity	kg 1.4-DB eq	1.68×10^{-3}	8.62
Marine aquatic ecotoxicity	kg 1.4-DB eq	3.53×10^6	2.14×10^5
Ozone layer depletion (ODP)	kg CFC-11 eq	1.26×10^{-3}	7.65×10^{-4}
Photochemical oxidation	kg C ₂ H ₄ eq	1.10	5.41×10^{-2}
Terrestrial ecotoxicity	kg 1.4-DB eq	9.30	4.53×10^{-1}

Also in this case, the relative results of the different water-treatment processes were reported. Figure 5 shows the results comparison between the innovative process with high and low silica amount and the use of bottled water.

As shown in the figure, it can be highlighted that the environmental impact of the optimized innovative process was significantly lower than the use of bottled water in all impact categories. The results confirm that the innovative process optimization which allows a decrease of the used active silica amount could reduce both the resource consumption and the environmental impact.

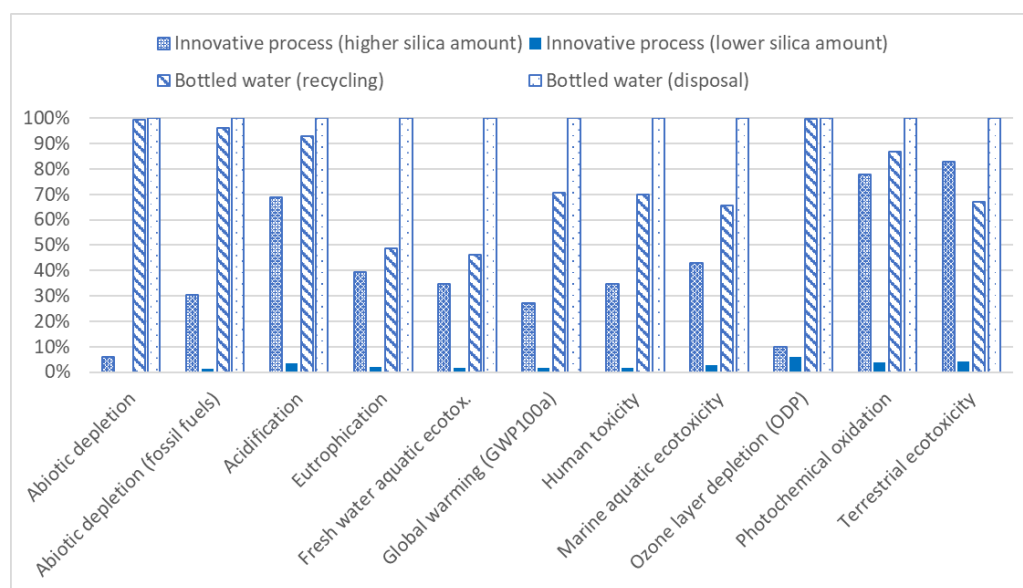


Figure 5. Potential environmental impact comparison among different water treatments: innovative process with higher amount of silica (27 kg/26 m³ of water) and lower amount of active silica (1.3 kg/26 m³ of water), use of bottled water with bottle recycling, and bottle disposal.

4. Conclusions

A life-cycle assessment (LCA) was carried out to evaluate the environmental impacts of a complete innovative process for water treatment developed in the framework of the LIFE LIBERNITRATE project. The analysis considered the production of ashes, the extraction and activation of silica, and the water treatment. The results were compared to the environmental impact derived from the use of bottled water, considering both recycled and landfill disposal scenarios.

The most environmentally impacting stage of the studied process was found to be the production of silica from the ashes of rice straw, which was highly affected by the chemical reagents used such as sulfuric acid, ethanol, ammonia and sodium hydroxide. These compounds generate significant impacts in the impact categories of acidification, eutrophication, and photochemical oxidation. The high level of the terrestrial ecotoxicity was due to these chemical compounds and also to the energetic consumption and the related electrical energy for their production. The LCA proved that the innovative process could contribute to reducing the environmental impact of water-treatment technologies resulting in lower environmental indicators with respect to the use of bottled water, both recycled and sent to landfill.

It is important to highlight that the new process has been studied at laboratory-scale, and during the process, scale-up the system is expected to be further optimised and made more efficient, for example reducing the amount of active silica used per day, consequently reducing the associated environmental and economic impacts. By reducing the quantity of used silica, the environmental impact could be reduced significantly (around 95%) in nearly all categories.

This circular strategy would help, on the one hand, in avoiding management difficulties and undesired uncontrolled combustion of rice straw and, on the other hand, could be applied to treat water in small towns where traditional water treatments (i.e., reverse osmosis) may not be available due to the high installation and operating costs, helping reduce (or avoid) the use of bottled water.

5. Patents

Patent N° 2727673—University of Genova, Universitat Politècnica de Valencia and Universitat de Valencia entitled *Procedimiento de adsorción de nitratos mediante sílice modificada activa a partir de ceniza de paja de arroz*.

Author Contributions: Conceptualization, methodology, software, validation, investigation, data curation, writing—original draft preparation, M.M.; data analysis, writing—original draft preparation, C.M.; resources, writing—review and editing, supervision, funding acquisition, E.A. All authors have read and agreed to the published version of the manuscript.

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References

1. FAOSTAT Food and Agriculture Organisation of the United Nations. Available online: <http://www.fao.org/home/en> (accessed on 18 January 2022).
2. MCS Europe's Water: An Indicator-Based Assessment. Available online: http://www.mcs-international.org/downloads/029_europes_water.pdf (accessed on 18 January 2022).
3. Commission to the Council and the European Parliament. *Council Directive 91/676/EEC*; Commission to the Council and the European Parliament: Brussels, Belgium, 2018.
4. European Parliament; Commission of the E.U. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Off. J. Eur. Parliam.* **2000**, *L327*, 1–82.
5. Baetge, S.; Kaltschmitt, M. Rice straw and rice husks as energy sources—Comparison of direct combustion and biogas production. *Biomass Convers. Biorefinery* **2018**, *8*, 719–737. [[CrossRef](#)]
6. Moliner, C.; Bosio, B.; Arato, E.; Ribes, A. Thermal and thermo-oxidative characterisation of rice straw for its use in energy valorisation processes. *Fuel* **2016**, *180*, 71–79. [[CrossRef](#)]
7. Sulyman, M.; Namiesnik, J.; Gierak, A. Low-cost Adsorbents Derived from Agricultural By-products/Wastes for Enhancing Contaminant Uptakes from Wastewater: A Review. *Polish J. Environ. Stud.* **2017**, *26*, 479–510. [[CrossRef](#)]
8. Ali, I.; Asim, M.; Khan, T.A. Low cost adsorbents for the removal of organic pollutants from wastewater. *J. Environ. Manag.* **2012**, *113*, 170–183. [[CrossRef](#)] [[PubMed](#)]
9. Eltaweil, A.S.; Omer, A.M.; El-Aqapa, H.G.; Gaber, N.M.; Attia, N.F.; El-Subruiti, G.M.; Mohy-Eldin, M.S.; Abd El-Monaem, E.M. Chitosan based adsorbents for the removal of phosphate and nitrate: A critical review. *Carbohydr. Polym.* **2021**, *274*, 118671. [[CrossRef](#)] [[PubMed](#)]
10. Khalid, S.N.; Ahmad, S.N.; Kiani, J.A. Removal of mercury from aqueous solutions by adsorption to rice husks. *Sep. Sci. Technol.* **1999**, *34*, 3139–3153. [[CrossRef](#)]
11. Kumar, U.; Bandyopadhyay, M. Sorption of cadmium from aqueous solution using pretreated rice husk. *Bioresour Technol.* **2006**, *97*, 104–109. [[CrossRef](#)] [[PubMed](#)]
12. Orlando, U.S.; Baes, A.U.; Nishijima, W.; Okada, M. Preparation of agricultural residue anion exchangers and its nitrate maximum adsorption capacity. *Chemosphere* **2002**, *48*, 1041–1046. [[CrossRef](#)]
13. Diagboya, P.N.E.; Dikio, E.D. Silica-based mesoporous materials; emerging designer adsorbents for aqueous pollutants removal and water treatment. *Microporous Mesoporous Mater.* **2018**, *266*, 252–267. [[CrossRef](#)]
14. Moliner, C.; Teruel-Juanes, R.; Primaz, C.; Badia, J.; Bosio, B.; Campíns-Falcó, P.; Molíns-Legua, C.; Hernandez, F.; Sanjuan-Navarro, L.; Madramany, P.; et al. Reduction of Nitrates in Waste Water through the Valorization of Rice Straw: LIFE LIBERNITRATE Project. *Sustainability* **2018**, *10*, 3007. [[CrossRef](#)]
15. Moliner, C.; Bove, D.; Arato, E. Co-Incineration of Rice Straw-Wood Pellets: A Sustainable Strategy for the Valorisation of Rice Waste. *Energies* **2020**, *13*, 5750. [[CrossRef](#)]
16. Robles-Jimarez, H.R.; Sanjuan-Navarro, L.; Jornet-Martínez, N.; Primaz, C.T.; Teruel-Juanes, R.; Molíns-Legua, C.; Ribes-Greus, A.; Campíns-Falcó, P. New silica based adsorbent material from rice straw and its in-flow application to nitrate reduction in waters: Process sustainability and scale-up possibilities. *Sci. Total Environ.* **2022**, *805*, 150317. [[CrossRef](#)] [[PubMed](#)]
17. European Commission. *ILCD Handbook: General Guide for Life Cycle Assessment—Detailed Guidance*; European Commission: Brussels, Belgium, 2010.
18. Silalertruksa, T.; Gheewala, S.H. A comparative LCA of rice straw utilization for fuels and fertilizer in Thailand. *Bioresour. Technol.* **2013**, *150*, 412–419. [[CrossRef](#)] [[PubMed](#)]

19. Horowitz, N.; Frago, J.; Mu, D. Life cycle assessment of bottled water: A case study of Green2O products. *Waste Manag.* **2018**, *76*, 734–743. [[CrossRef](#)] [[PubMed](#)]
20. Acero, A.P.; Rodríguez, C.; Ciroth, A. *LCIA Methods: Impact Assessment Methods in Life Cycle Assessment and Their Impact Categories*; GreenDelta: Berlin, Germany, 2015.
21. Garfi, M.; Cadena, E.; Sanchez-Ramos, D.; Ferrer, I. Life cycle assessment of drinking water: Comparing conventional water treatment, reverse osmosis and mineral water in glass and plastic bottles. *J. Clean. Prod.* **2016**, *137*, 997–1003. [[CrossRef](#)]
22. Liu, Z.; Xu, A.; Long, B. Energy from Combustion of Rice Straw: Status and Challenges to China. *Energy Power Eng.* **2011**, *3*, 325–331. [[CrossRef](#)]
23. Singh, G.; Gupta, M.K.; Chaurasiya, S.; Sharma, V.S.; Pimenov, D.Y. Rice straw burning: A review on its global prevalence and the sustainable alternatives for its effective mitigation. *Environ. Sci. Pollut. Res.* **2021**, *28*, 32125–32155. [[CrossRef](#)]
24. Singh, A.; Basak, P. Economic and environmental evaluation of rice straw processing technologies for energy generation: A case study of Punjab, India. *J. Clean. Prod.* **2019**, *212*, 343–352. [[CrossRef](#)]