Biological nitrate removal from a drinking water supply with an aerobic granular sludge technology: An environmental and economic assessment

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ABSTRACT

Nitrate pollution of groundwater, mainly from agricultural applications, is a widespread water quality problem in many countries. The aim of this study was to identify and compare the main environmental impacts and costs associated with removing nitrate from groundwater under a conventional treatment technology and a technology based on a biological treatment process (denitrification using aerobic granular sludge). The analysis focused on the first real-world experience of an industrial-scale implementation of said technology, applied to the drinking water supply in a small town in Spain. The methods selected for the environmental and economic evaluations were life cycle assessment and cost-effectiveness analysis, respectively. The drinking water treatment technologies under study were a conventional reverse osmosis plant and a plant using a biological treatment called ecogranularwater. The analysis of these two drinking water production processes was divided into two phases: structure and water treatment. This study demonstrates that the biological technology produces drinking water in a more environmentally-friendly, cost-effective way, and with lower energy costs. The greatest environmental impacts from the reverse osmosis technology occurred in the water treatment phase due to the high levels of energy consumption (up to 1.68 kWh m^{-3} higher than with the ecogranularwater technology). In the structure phase, the biological technology contributed more than reverse osmosis in all impact categories, with values ranging from 91% in freshwater ecotoxicity to 98% in stratospheric ozone depletion. The cost of producing 1 m^3 of water was estimated as 43% lower with the ecogranularwater technology compared to reverse osmosis. In order to further lessen the environmental impact of the biological technology, efforts should be focused on reducing and optimizing energy use and making improvements to the design of the structure. This biological technology proved a good alternative for small and medium-sized municipalities with problems of nitrate-polluted water. The decision to apply technological innovations in drinking water treatments to remove nitrates can be supported by environmental and economic studies.

Keywords: Life cycle assessment, Nitrate-polluted water, Drinking water, Environmental footprint, Cost-effectiveness analysis, Biological treatment

1. INTRODUCTION

The constant release of chemicals into water bodies is leading to a deterioration in the quality of our water resources. These chemicals include emerging water contaminants such as pharmaceutical product residues, as well as pollutants from dyes, fertilizers and pesticides, all of which pose serious problems to human health and the environment (Ali et al., 2018; Basheer, 2018; Basheer and Ali, 2018). Groundwater is one of the main sources of drinking water in most countries, especially in arid and semi-arid climates. Groundwater pollution, caused by the release of chemicals such as nitrogen into the ground, is a major issue these days. Nitrogen (N) losses lead to increased nitrate concentrations in aquifers and the eutrophication of rivers, lakes, and transition surface waters (Smith, 2003; Smith and Schindler, 2009). Since 1990, the nitrogen surplus in Spain has been growing, mainly due to inadequate irrigation and fertilization management (EEA, 2006). Agriculture is responsible for potentially high levels of N loss, whether through nitrate leaching (Pratt, 1984; Ramos et al., 2002; Thompson et al., 2007; Guo et al., 2010), gaseous losses or large quantities of N left in the soil after the crop harvest, which can be washed out by the rains falling between consecutive crops. Some studies point to the reduction and optimization of fertilization as the most efficient way to improve the environmental performance of crop production (Romero-Gámez et al., 2020).

Certain areas in Spain are classified as zones that are at risk of agricultural nitrate pollution (Nitrate Vulnerable Zones or NVZs), according to the European Union directive on measures to prevent aquifer contamination by fertilizers (CEC, 1991). This directive contains mandatory measures relating to agricultural practices, aimed at reducing nitrate pollution of groundwater and surface water. It establishes a limit for the concentration of nitrates in drinking water of 25 milligrams per litre (mg L^{-1}). The present study is focused on an area designated an NVZ, specifically, the municipality of Torre-Cardela (north-central area of Granada province, Andalusia, Spain), where water for human consumption is taken exclusively from the aquifer.

In Torre-Cardela, as in many other municipalities in Spain, the management of the municipal water service gives rise to both environmental and economic problems. Regarding the environmental problems, in addition to the fact this area is classified as an NVZ (BOJA, 2020), the Torre-Cardela reverse osmosis plant consumes 1.42 m^3 of raw water to produce 1 m^3 of water, meaning that 42% of the treated water is being rejected. This is a serious issue in a Mediterranean region facing water scarcity, recurring droughts and threats from climate change. On top of this is the high energy consumption required for the process (around 2 kilowatt-hour (kWh) per m^3 produced) and, to a lesser extent, the chemicals used in the process. The economic problem is basically that the financial costs of the service, that is, the investment costs and the operating and maintenance costs are not being covered. Moreover, environmental and opportunity costs are not considered. According to our own estimates based on data provided by the town council, only 60% of the financial costs of the service are covered through the revenue generated by urban water tariffs.

In response to these problems, a new alternative for treating drinking water in the study area was developed and optimized. The new treatment is based on aerobic granular sludge technology (nitrate removal by means of heterotrophic microbial metabolism in granular biomass). This biological technology applies the lowest concentration of carbon source needed to remove nitrates at concentrations higher than 25 mg L^{-1}, which determines the eukaryotic and prokaryotic microorganisms involved in the denitrification process, as well as the granular stability (Hurtado-Martínez et al., 2021a). Aerobic granular sludge systems require 25-50% less floor space than a conventional wastewater treatment system, use 25-40% less electricity than a conventional activated sludge system, and their operating costs are 20-25% lower (Sarma et al., 2017). Biological drinking water treatment systems are considered environmentally-friendly, cost-effective systems because the processes are carried out by heterotrophic or autotrophic microorganisms. However, biological technologies may also present some problems due to their operating conditions and the initial investment or maintenance costs of the bioreactors (Ahmed et al., 2017). Various different strategies have been applied in biological wastewater treatment technologies to achieve a successful nitrate removal rate, such as the use of external carbon sources in anoxic reactors (Panepinto et al., 2013).

Denitrification of groundwater to ensure safe nitrate levels can be done through either separation- or removal-type technologies. Separation technologies include ion exchange, nanofiltration, electrochemical reduction, and reverse osmosis (Rezvani et al., 2019). However, the generation of brine as a secondary waste product and high operational costs are disadvantages compared to removal-type methods, which completely remove nitrates by converting them to dinitrogen. Removal-type methods can be based on chemical and/or biological processes. Some of the chemical and physical technologies used to remove nitrates and other contaminants (e.g., pharmaceutical residues or heavy metal ions) from water include metal nanoparticles (Adeleye et al., 2016; Ali et al., 2018, 2019; Shahat et al., 2018), electrodialysis (Martínez et al., 2017), ion exchange adsorption (Awal, 2019; Kamel et al., 2019), reverse osmosis (Epsztein et al., 2015), chemical reduction (Eljamal et al., 2020a, 2020b) and catalytic and electrocatalytic reduction

(Siciliano, 2015; Hashim et al., 2017). However, chemical and physical processes have high start-up and operating costs, as well as high energy requirements, which is an obstacle to their implementation in small population centres.

Reliable environmental assessment tools are therefore needed to determine the level of environmental sustainability of these processes used to produce water for human consumption. The life cycle assessment (LCA) concept is used to analyse the environmental impact of industrial products or production process, as well as for the evaluation of treatment processes (Ortiz et al., 2007; Vince et al., 2008). Several studies have used the LCA methodology to assess the environmental impacts of different water treatment technologies, especially for making an objective comparison between alternative and conventional desalination processes (Muñoz and Rodríguez, 2008; Vince et al., 2008; Tarnacki et al., 2011; Zhou et al., 2011; Qiu and Davies, 2012; Lawler et al., 2015). Previous studies have concluded that the choice of water treatment chemicals and the energy source are critical elements in the LCA of the production of drinking water from groundwater and fresh surface water since energy consumption and chemical dosing have high environmental impacts in different processes. Thus, several authors find that the construction and infrastructure of the plants have less of an impact than the operational phase (Friedrich et al., 2001; Raluy et al., 2005; Stokes and Horvath, 2006; Bonton et al., 2012).

The environmental impacts of production processes usually remain in the background, with economic profitability being prioritized; however, this framework no longer reflects the scientific and social reality. It is important to carry out a rigorous comparative assessment of different production systems in terms of their environmental and economic impact. Society is becoming increasingly aware of environmental concerns and sustainability in general. There is thus a need for integrated environmental and economic LCA of drinking water systems (Bonton et al., 2012). The design and implementation of cost-effective, environmentally-friendly production processes is a fundamental challenge that must be tackled to ensure the sustainability of agricultural systems and ecosystem services. Therefore, the aim of this work is to design a sustainable, high-quality product and service to meet societal demand.

To that end, the present study conducts a comparison of the environmental impacts and costs associated with two technologies for removing nitrate from groundwater: 1) a physical-chemical technology (reverse osmosis, RO) and 2) a biological technology (ecogranularwater, EGW). To compare the two technologies, LCA and an economic impact analysis are carried out. To the best of our knowledge, the new biological plant under study—a pilot plant that supplies nitrate-free water to a Spanish municipality—is the first of its kind built on an industrial scale. Furthermore, the present study is the first environmental and economic analysis to include the most relevant elements of both technologies. A major contribution of this study is that it provides detailed information on nitrate removal technologies for use in municipalities classified as NVZs, facing serious environmental and economic problems related to the management of the municipal water service.

2. MATERIALS AND METHODS

2.1. ENVIRONMENTAL IMPACT ASSESSMENT

LCA was used to evaluate the environmental footprint of drinking water production, in accordance with the European Commission recommendation on the use of common methods to measure and communicate the life cycle environmental performance of products and organizations (2013/179/EU) and the standards ISO 14040 and 14044 (2006). LCA is a very useful methodology for measuring the environmental performance of a process and/or product, since it allows us to evaluate the associated environmental loads and to determine the impact on the environment of its use of resources, materials and energy inputs, and emissions. The main function of LCA is to support decision-making about a process and/or product, and more specifically, to offer an understanding of its possible environmental consequences. In addition, LCA can inform the implementation of environmental improvement strategies. There are four main stages in an LCA study according to ISO 14040: a) goal and scope definition, b) inventory analysis, c) impact assessment and d) interpretation of the results. This work includes the mandatory phases (classification and characterization) and the optional phase (normalization) of impact assessment, as defined by the ISO standard.

2.1.1. GOAL AND SCOPE DEFINITION

The main aim of this study was to calculate and compare the environmental footprint of two drinking water production technologies. More specific objectives were: (i) to conduct a life cycle inventory (LCI) with all the flows and processes involved in the selected drinking water production plants; (ii) to identify the processes and phases that produce the most significant environmental issues; and (iii) to design and propose to users a more efficient, environmentally-friendly production system, while at the same time suggesting possible strategies for mitigating the environmental impact.

The scope of this study was the production of drinking water, considering all the input and output flows of materials and energy up to the point where the water has been treated for human consumption. According to the Product Category Rule (PCR) for water distribution through the mains, the unit of analysis is the production of 1 m^3 of water fit for human consumption. Therefore, the functional unit (FU) was defined as 1 m^3 of drinking water.

The study compared two drinking water treatment technologies: a conventional plant with RO water treatment and a new plant using a biological treatment called ecogranularwater (EGW). The analysis focused on both the structure of each plant and the water treatment process. The system boundary was set at the intake to both plants without considering the pumping from the raw water tank, since this configuration may differ depending on where the facilities are located and could distort the results in relation to energy consumption and thus the impacts. Therefore, the LCA focused exclusively on the production of 1 m^3 of water fit for human consumption, produced by a biological process and by RO.

The environmental analysis of the production of drinking water by the two technologies included the following elements: the transport, manufacture and waste management of the materials used in the infrastructure of the two technologies; the chemicals used in the production of the water; the raw water consumed in the production of 1 m^3 of drinking water; the reject water in the RO technology only, since no water is rejected in the EGW technology; the energy consumed during the production process; and the emission of chemicals into the reject water. The analysis did not include the bacteria rejected in the sand filter of the EGW technology since it was deemed to have little or no environmental impact compared to the other elements included, as reported in previous studies (Muñoz and Rodríguez Fernández-Alba, 2008). Figure 1 is a flow chart of the water production technologies considered, structured in two phases (plant infrastructure and water treatment), each showing the processes and flows. This chart facilitates inventory analysis, impact analysis and interpretation of the study results.

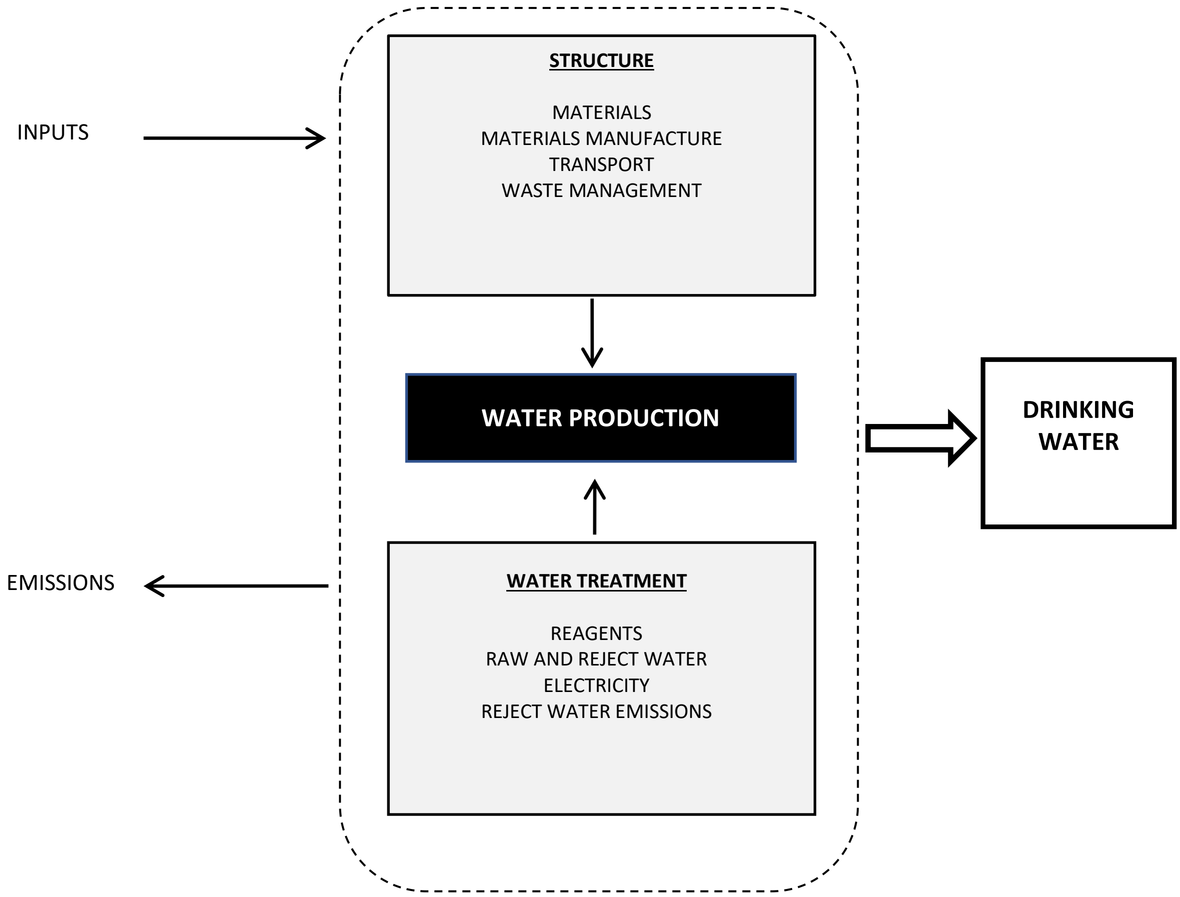

Fig.1. Flow diagram of the phases analysed in each drinking water production technology

2.1.2. LIFE INVENTORY ANALYSIS

The data on the two drinking water production technologies evaluated were collected through different suppliers, literature, experimental data, and direct measurements, and in some cases were tested to check the accuracy of the data. The life cycle inventory (LCI) included representative local data from the two production plants in the municipality of Torre-Cardela, Granada (Spain), the geographical coordinates of which are 37°30' N, 3°21' W**.**

The inventory data on the RO technology were collected from the town council's billing information on technology inputs and direct readings of the rotameters, electricity meter and chemical dosing systems. For the infrastructure, direct measurements were made of the materials used. For the EGW technology, the inventory was based on direct readings of electricity consumption provided through the monitoring carried out in this plant, information on the chemicals was obtained from the concentrations applied in the production process, and the information on water used was sourced from the measurement of the water in the cleaning filter. Infrastructure data were taken from direct measurements in the plant.

The inventory data collected span the period from 2019 to 2021. Data collected for each phase were related to materials and energy consumption, emissions into the water and atmosphere, and the waste generated. All data for the environmental analysis were obtained from the Ecoinvent database v. 3.7.1. (Ecoinvent, 2021), including data on the manufacture of materials needed to install the infrastructure, manufacture of chemicals, electricity production mix, and materials and waste transport and disposal. The emissions of chemicals into the RO reject water were measured directly in the laboratory.

The LCA involved the abovementioned data collection to quantify the relevant inputs and outputs during the life cycle of the drinking water production process of each technology. The main characteristics of these technologies are shown in Table 1.

Table 1. Main characteristics of selected drinking water production technologies

	REVERSE OSMOSIS	**ECOGRANULARWATER**
Drinking Water (m^3 h^{-1})	4	1.6
Production period (hours)	1	2
Raw Water (m^3 h^{-1})	1.42	1.02
Reject water (m^3 h^{-1})	0.42	0.02
Electricity consumed (KWh m^{-3})	2.05	0.37

The analysis of the drinking water production process was divided into two phases (structure and water treatment) to facilitate data compilation, the assessment, and the interpretation of the results. The detailed quantitative data for all the materials and processes related to the structure and the chemicals included in the water treatment are summarized in Tables 2, 3, 4, 5 and 6.

2.1.2.1. STRUCTURE

The main components of the RO technology structure were the metal frame, two pressure vessels, a pressure pump and polyvinylchloride (PVC) pipes. The EGW structure was composed of a metal frame, three bioreactors—one of which was made of polymethyl methacrylate (PMMA) and the other two of glass fibre reinforced plastic (GFRP)—designed as a cylindrical sequential batch reactor, pumps and blowers.

The materials used in the manufacture of the elements of the RO and EGW technologies were included in this phase of the analysis (Tables 2 and 3, i.e., high density polyethylene (HDPE), steel, polycarbonate (PC), polypropylene (PP), GFRP, PVC etc. used in pipes, frames, clamps, filters, membranes, tanks, pumps, sensors, and reactors. The materials used in both structures were raw materials, so the analysis also accounted for manufacturing processes such as blow moulding, metal product manufacturing and plastic extrusion. In addition, this phase of the analysis included the extraction and transport of each material by truck to the production sites, as well as the management and transport by truck of waste materials (metal and plastic) to landfill and recycling centres (Tables 2 and 3) (BOJA, 2012).

Table 2. Materials and processes for the reverse osmosis technology structure included in the life cycle inventory

Materials	Elements	Quantity*	Unit
PVC	Pipes	50.49	kg
Galvanized steel	Structure and frame	173.11	kg
Stainless steel	Clamps and pressurizer	191.30	kg
HDPE	Filters and tanks	13.68	kg
GFRP	Vessels	64.10	kg
PP	Membranes	23.04	kg

Materials	Processes	Quantity*	Unit
PVC	Extrusion, plastic pipes	50.49	kg
Steel	Manufacturing, metal working	364.41	kg
HDPE	Blow moulding, tanks	12.18	kg
Transport of materials to the production sites	freight, lorry 7.5-16 metric ton	33.10	tkm

Materials	Waste	Quantity*	Unit
PVC	recycling centre	50.49	kg
Galvanized steel	recycling centre	173.11	kg
Stainless steel	recycling centre	191.30	kg
HDPE	recycling centre	13.68	kg
GFRP	landfill	64.10	kg
PP	recycling centre	23.04	kg
Transport of waste to the recycling centre	freight, lorry 7.5-16 metric ton	28.8	tkm
Transport of waste to landfill	freight, lorry 7.5-16 metric ton	2.72	tkm

*total amount of material without considering life span

PVC: polyvinylchloride; HDPE: high density polyethylene; GFRP: glass fibre reinforced polyester; PP: polypropylene; tkm: tonne-kilometre

Table 3. Materials and processes for the ecogranularwater technology structure included in the life cycle inventory

Materials	Elements	Quantity*	Unit
PVC	Pipes and dosing system	31.93	kg
Brass	Pipes	3.30	kg
Rubber	Pipes and clamps	5.64	kg
Galvanized steel	Frame, tramex	298.00	kg

Stainless steel	Pumps, reactor 1 and blowers	145.83	kg
Zinc plated steel	Clamps	4.45	kg
Carbon steel	Sand filter	80.00	kg
PC	Sensor and transmitters	4.28	kg
HDPE	Tanks	42.00	kg
GFRP	Reactor 2 and 3	1700.00	kg
PMMA	Reactor 1	27.53	kg

Materials	**Processes**	**Quantity***	**Unit**
PVC	Extrusion, plastic pipes	31.93	kg
Steel	Manufacturing, metal working	528.28	kg
HDPE	Blow moulding, tanks	29.90	kg
Transport of materials to the production sites	freight, lorry 7.5-16 metric ton	544.41	tkm

Materials	**Wastes**	**Quantity***	**Unit**
PVC	recycling centre	31.93	kg
Brass	recycling centre	3.30	kg
Steel	recycling centre	528.28	kg
HDPE	recycling centre	42.00	kg
Rubber	landfill	5.64	kg
PC	landfill	4.28	kg
GFRP	landfill	1700.00	kg
PMMA	landfill	27.53	kg
Transport of waste to the recycling centre	freight, lorry 7.5-16 metric ton	37.77	tkm
Transport of waste to landfill	freight, lorry 7.5-16 metric ton	73.84	tkm

*total amount of material without considering life span

PVC: polyvinylchloride; HDPE: high density polyethylene; GFRP: glass fibre reinforced polyester; PC: polycarbonate; PMMA: polymethyl methacrylate; tkm: tonne-kilometre

The time periods considered for the environmental assessment of the frame materials (average life span for the remaining plastic and metal materials) are shown in Table 4.

Table 4. Life span of structure materials used in the reverse osmosis and ecogranularwater technologies (years)

REVERSE OSMOSIS

Materials	**Life span (years)**
PVC	50
Stainless steel	100
HDPE	50
PRFV	120

Galvanized steel	50

ECOGRANULARWATER

Materials	Life span (years)
PVC	50
Brass	50
Rubber	30
Galvanized steel	70
Zinc plated steel	60
PC	25
PMMA	40
Stainless steel	100
Carbon steel	60
Steel	65
HDPE	60
PRFV	120

PVC: polyvinylchloride; HDPE: high density polyethylene; GFRP: glass fibre reinforced polyester; PP: polypropylene; PC: polycarbonate; PMMA: polymethyl methacrylate

2.1.2.2. WATER TREATMENT

The RO technology inputs included in this phase were the chemicals used (polycarboxylates and hydrochloric acid manufacturing) (Table 5), the raw water needed to generate the permeate water and the energy consumed in the water treatment process (Table 1). The chemical composition of the water from discharge was determined, and the emissions to water were included in the analysis (Table 5).

Table 5. Chemical compound added to raw groundwater and emissions to reject water in the reverse osmosis technology per FU (m^{-3})

Chemicals	**g/m^3**
Polycarboxylates	32.9
Hydrochloric acid, HCl	27.5

Water emissions	**g/m^3**
Nitrate, NO^{3-}	5.23E+01
Chlorides, Cl^-	1.52E+01
Calcium, Ca	8.77E+01
Magnesium, Mg	2.10E+01
Fluorides, F^-	2.68E-01

Nickel, Ni	1.03E-03
Potassium, K	9.47E-01
Silicon, Si	6.59E+00
Sodium, Na	7.82E+00
Sulfates, SO_4^{2-}	4.98E+01

The drinking water production process of the EGW technology involves the biological removal of nitrates by aerobic denitrifying bacteria that form a granular sludge in a sequencing reactor. Granular aerobic systems for drinking water treatment are based on the ability of microorganisms to degrade pollutants such as nitrate in groundwater. The operation of these systems relies on the metabolism of different microorganisms, including denitrifying bacteria such as *Pseudomonas*. These bacteria can carry the nosZ gene in their genome, which encodes nitrous oxide reductase, an enzyme responsible for the conversion of nitrous oxide (N_2O) to dinitrogen (N_2) (Eljamal et al., 2020b). Achieving an optimal nitrate removal process in an oligotrophic medium such as groundwater requires the addition of an external carbon source to the system, as it enables the complete denitrification process to occur correctly. There are many carbon sources that can be used, including sodium acetate, a compound that has proven effective in the biological nitrate removal process (Hurtado-Martínez et al., 2021b).

The C:N ratio is of vital importance in the removal process, and it has to be adjusted according to the nature of the water to be treated (Hurtado-Martinez et al., 2021a). In the case of nitrate-contaminated groundwater with 50 to 100 mg NO_3^- L^{-1}, a lower C:N ratio will lead to the formation of smaller and denser granules, enabling efficient removal in compliance with the European Water Framework for drinking water. For higher concentrations of nitrate-contaminated groundwater (>120 mg NO_3^- L^{-1}), C:N needs to be higher to ensure better removal. In this case, the size of the granules will be larger but the distance from the outer layer to the core of the granules allows a strong gradient of oxygen and nutrients, as occurs with a low C:N. The optimal mode of operation depends entirely on the in situ groundwater conditions, although general guidelines can be given; for example, the C:N ratio should range from a minimum of 1 to a maximum of 4 (Hurtado-Martínez et al., 2021a).

The main system inputs analysed were the chemicals used to maintain the bacterial communities present in the biological reactor: namely, sodium acetate ($C_2H_3NaO_2$), potassium chloride (KCl), magnesium sulfate heptahydrate ($MgSO_4{\cdot}7H_2O$), potassium dihydrogen phosphate (KH_2PO_4) and potassium monohydrogen phosphate (K_2HPO_4) (Table 6). There was practically no reject water in this process: the only reject water was that generated in the washing of the sand filter, which was done once a day in this pilot plant. It is estimated that in a plant on a larger industrial scale, an even smaller volume of reject water would be produced. Given the negligible volume of reject, it was discharged into a small wetland area created for that purpose; hence, the impact is not significant. The raw water needed to generate the permeate water and the energy consumed were also included in the analysis (Table 1).

Table 6. Doses of chemicals compounds added to groundwater in the ecogranularwater technology per FU (m^{-3})

Reactive	g/m^3
Sodium Acetate, $C_2H_3NaO_2$	100
Potassium chloride, KCl	2.6
Magnesium sulfate heptahydrate, $MgSO_4{\cdot}7H_2O$	6.3
Potassium monohydrogen phosphate, K_2HPO_4	6.1
Potassium dihydrogen phosphate, KH_2PO_4	1.5

2.1.3. LIFE CYCLE IMPACT ASSESSMENT (LCIA)

The production burdens associated with drinking water production were calculated and evaluated using the LCIA methodology. The simaPro software v. 9.2.0.2 (PRé Sustainability, 2021) was used to model the systems and evaluate the environmental impacts, considering the classification, characterization and normalization stages set out in ISO 14040 (2006), which specifies the general framework, principles, and basic requirements to carry out an LCA. The LCIA was performed using a midpoint approach. The method used for the classification, characterization and normalization of the inputs and outputs of the inventory was the ReCiPe Midpoint (H) (Huijbregts et al., 2017). The six midpoint impact categories included in this study are shown in Table 7. These environmental impacts were chosen because of their relevance in energy and industrial processes, and in accordance with the PCR for water distribution through the mains included in the International Environmental Product Declaration (EPD) Systems (Environdec, 2021).

Table 7. Selected environmental impacts and units of measurement

Impact category	Units
Carbon footprint	kg CO_2eq
Stratospheric ozone depletion	kg CFC-11 eq
Ozone formation, Terrestrial ecosystems	kg NO_x eq
Terrestrial acidification	kg SO_2 eq
Freshwater Eutrophication	kg P eq
Freshwater Ecotoxicity	kg 1,4-DCB

eq: equivalent; CO_2: carbon dioxide; CFC: chlorofluorocarbon; NOx: nitrogen oxides; SO_2: sulfur dioxide; P: phosphorus; DCB: dichlorobenzene

2.2. ECONOMIC IMPACT ASSESSMENT

The RO plant began operating in 2012 and from the beginning the service ran at a deficit, with tariff revenues only covering around 60% of the financial costs of the service. As the municipal drinking water service was managed directly by the Torre-Cardela town council itself, the remaining 40% was subsidized using other sources of municipal income. Therefore, it did not comply with the principle of cost recovery established in the Water Framework Directive (EU, 2000).

For the economic impact analysis, a cost-effectiveness analysis was carried out. Cost-effectiveness analysis is an instrument used in River Basin Plans to design the action programme to be applied in each river basin. It is the method most used to choose the policy measures aimed at ensuring the good ecological status of water bodies, as indicated by the Water Framework Directive (Berbel et al., 2011). Cost-effectiveness analysis is used to estimate the monetary cost needed to achieve a water policy objective measured in physical terms. This method can be used to identify the measures that enable the same objective to be achieved at a lower cost.

In this case, the cost of producing 1 m^3 of water with each of the technologies was compared. In a first stage, only the financial costs of the service were considered. In a second stage, environmental and resource costs were also included, as stipulated by the Water Framework Directive. The operating costs considered were personnel costs, the costs of reagents (Table 8) and energy costs. In addition, the costs of the membranes and filters used in RO were included in the analysis.

Table 8. Detail of the costs of reagents.

REVERSE OSMOSIS			
REAGENTS	**g/m^3**	**COST (€/kg)**	**UNIT COST (€/m^3)**
Polycarboxylates	32.97	12	0.3956
HCl	27.50	1	0.0275
TOTAL			**0.4231**

ECOGRANULARWATER			
REAGENTS	**g/m^3**	**COST (€/kg)**	**UNIT COST (€/m^3)**
Sodium acetate (CH_3COONa)	100	3.27	0.330
Magnesium sulfate heptahydrate ($MgSO_4*7H_2O$)	6.3	1.49	0.010

Potassium monohydrogen phosphate (K_2HPO_4)	6.1	3.64	0.020
Potassium dihydrogen phosphate (KH_2PO_4)	1.5	2.48	0.003
Potassium chloride (KCl)	2.6	2.02	0.010
TOTAL			**0.367**

To calculate the investment cost per m³ of water, the equivalent annual cost (EAC) of the investment was estimated using the following expression (Confederación Hidrográfica del Guadalquivir, 2015):

$$EAC = M\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right]$$

M: Initial investment for the construction of the plant.
i: Discount rate.
n: Useful life of the structure.

The calculation of the EAC was based on a discount rate of 2% and a useful life of 20 years. In the case of the RO technology, the initial investment was 64,500 euros, while in the biological plant it was 60,000 euros.

In addition, the estimation of the cost of the investment per m³ of water was based on an average consumption of 133 litres per person per day. This is the average daily consumption of water per person in Spain according to data from the Spanish Statistics Institute (2020).

In a second stage, as mentioned above, environmental costs and resource costs were incorporated into the analysis. In comparative terms, the main environmental impact to consider was from the reject water generated in the production process. The impact was practically negligible in the case of the pilot EGW plant: the percentage of reject water was only 2% and due to its composition it does not have a negative impact on the environment. However, the high volume of reject water generated in the RO technology does have a negative environmental impact since it is brine. The estimation of this environmental cost followed a preventive approach: specifically, the cost of treating 1 m^3 of wastewater was calculated. In this study, the value proposed was 0.31 €/m^3 (Moral Pajares et al., 2019).

The cost of the resource was represented by the alternative use value of the raw water rejected in the production process. Considering this opportunity cost makes sense in a hydrographic basin subject to high water stress. The Guadalquivir River Basin Authority estimates the opportunity cost at 0.354 €/m^3 (Confederación Hidrográfica del Guadalquivir, 2022).

3. RESULTS

3.1. ENVIRONMENTAL IMPACT ASSESSMENT

Table 9 shows the main impacts of the production of 1 m^3 of drinking water with the two water treatment technologies under analysis. RO produced higher environmental impacts than the new EGW technology for all impact categories, with differences ranging from 1.66E-03 kg NOx eq. in the ozone formation category to 6.18E-02 kg 1.4-DCB in the freshwater ecotoxicity category (Table 9a). These differences can be attributed to the higher electricity consumption in the water treatment phase in RO (up to 1.68 kWh m^{-3} higher than with the EGW technology), although the EGW technology produced a much smaller volume of drinking water per hour (Table 1). Freshwater ecotoxicity was the category with the highest impacts for both technologies, followed by the carbon footprint category in RO and by freshwater eutrophication in EGW (Table 9b).

Table 9. Comparison of the main impacts of the production of 1 m^3 of drinking water with the two water treatment technologies: a) characterized indicator results; b) normalized indicator results

Impacts per m^3 FU		**RO**	**EGW**
a)			
Carbon footprint	kg CO_2 eq	8.53E-01	3.76E-01
Stratospheric ozone depletion	kg CFC11 eq	4.10E-07	2.14E-07
Ozone formation, Terrestrial ecosystems	kg NO_x eq	2.71E-03	1.05E-03
Terrestrial acidification	kg SO_2 eq	4.88E-03	1.57E-03
Freshwater eutrophication	kg P eq	3.61E-04	1.13E-04
Freshwater ecotoxicity	kg 1,4-DCB	8.31E-02	2.13E-02
b)			
Carbon footprint		1.07E-04	4.70E-05
Stratospheric ozone depletion		6.85E-06	3.57E-06
Ozone formation, Terrestrial ecosystems		1.52E-04	5.90E-05
Terrestrial acidification		1.19E-04	3.83E-05
Freshwater eutrophication		5.55E-04	1.74E-04
Freshwater ecotoxicity		3.30E-03	8.46E-04

In both technologies, the water treatment phase contributed more to all impact categories than the structure phase, due to the application of chemical doses and energy consumption during the treatment processes (Tables 5 and 6). Table 10 shows the most relevant elementary flow, compartment, main life cycle phase, and main processes in RO and EGW for each impact category. Emissions related to inputs in the water treatment phases, mainly due to chemical compounds added and electricity consumed, were the main contributors to the impact categories studied. The carbon footprint impact was predominantly driven by carbon dioxide emissions to air caused by the electricity consumed in the RO treatment and the application of organic chemical compounds in the EGW treatment. Stratospheric ozone depletion was determined by dinitrogen monoxide emissions to air due to inputs such as the electricity consumed in RO and inorganic chemical compounds added to raw groundwater in the EGW treatment. The ozone formation category was primarily driven by nitrogen oxide emissions to air (mainly caused by the electricity consumed) and the application of organic chemical compounds, in RO and EGW technologies, respectively. Sulfur dioxide emissions to air and phosphate and copper emissions to groundwater from the electricity consumed during the water treatment process in both technologies were major pollutants in the terrestrial acidification, freshwater eutrophication and freshwater ecotoxicity categories, respectively.

Table 10. Most relevant elementary flow, compartment, main life cycle phase, and main processes for each impact category

Impact category	**Elementary flow**	**Compartment**	**Main LC phase**	**Main process RO**	**Main process EGW**
Carbon footprint	Carbon dioxide, CO_2	Air	Water treatment	Electricity (92.71%)	Chemicals, organic (55.64%)
Stratospheric ozone depletion	Dinitrogen monoxide, N_2O	Air	Water treatment	Electricity (89.65%)	Chemicals, inorganic (40.44%)
Ozone formation, Terrestrial ecosystems	Nitrogen oxides, NO_x	Air	Water treatment	Electricity (95.55%)	Chemicals, organic (50.33%)
Terrestrial acidification	Sulfur dioxide, SO_2	Air	Water treatment	Electricity (96.20%)	Electricity (54.83%)
Freshwater Eutrophication	Phosphate, PO_4^{3-}	Groundwater	Water treatment	Electricity (91.18%)	Electricity (53.36%)
Freshwater Ecotoxicity	Copper, Cu	Groundwater	Water treatment	Electricity (94.44%)	Electricity (67.79%)

Figure 2 shows the contributions to all impact categories of the water treatment phases of the RO and EGW technologies. EGW had lower environmental impacts than RO for all impact categories. The greatest impacts of the RO water treatment phase were registered in the acidification (76%), eutrophication (76%) and ecotoxicity (80%) categories, due to the emissions to air and groundwater, mainly caused by the electricity consumed (Table 10). Organic and inorganic chemical compounds added in the water treatment phase in the EGW technology (Table 6) were the inputs accounting for its greatest impacts in the carbon footprint and stratospheric ozone categories (contributing approximately 31%).

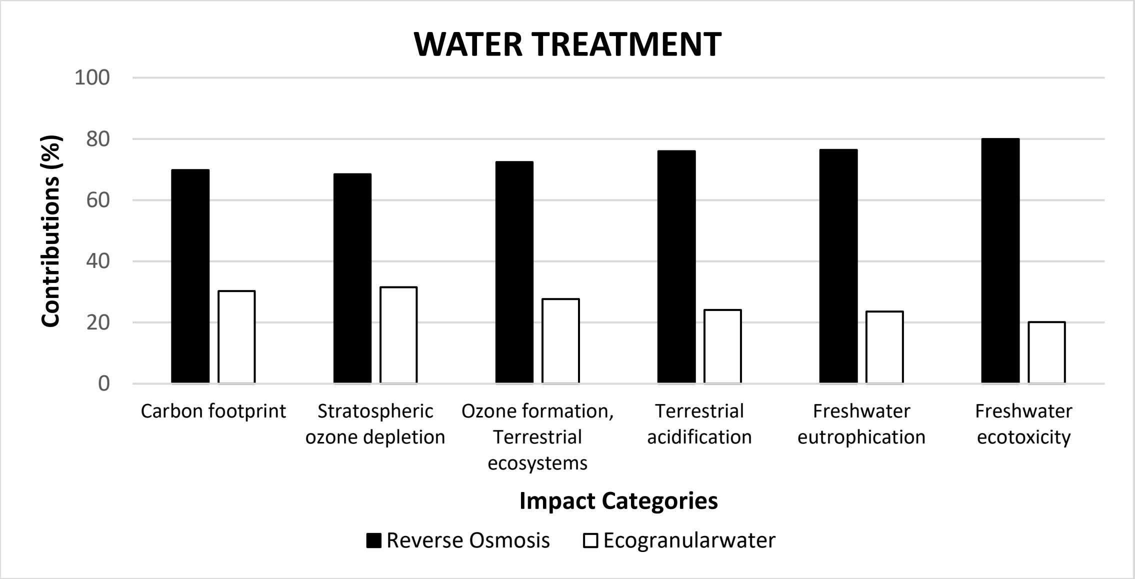

Fig. 2. Contributions of the two technologies to selected impact categories for the water treatment phase

Conversely, in the structure phase, EGW technology contributed more than RO for all impact categories, with values ranging from 91% in freshwater ecotoxicity to 98% in stratospheric ozone depletion. The large amount of materials used in the installation of the EGW plant was the main cause of the high impacts in all categories (Table 3). Specifically, GFRP—the material used in biological reactors 2 and 3—made the greatest contribution in terms of the emissions produced in most categories, with maximum values of 97% and 70% in the stratospheric ozone depletion and ozone formation categories, respectively.

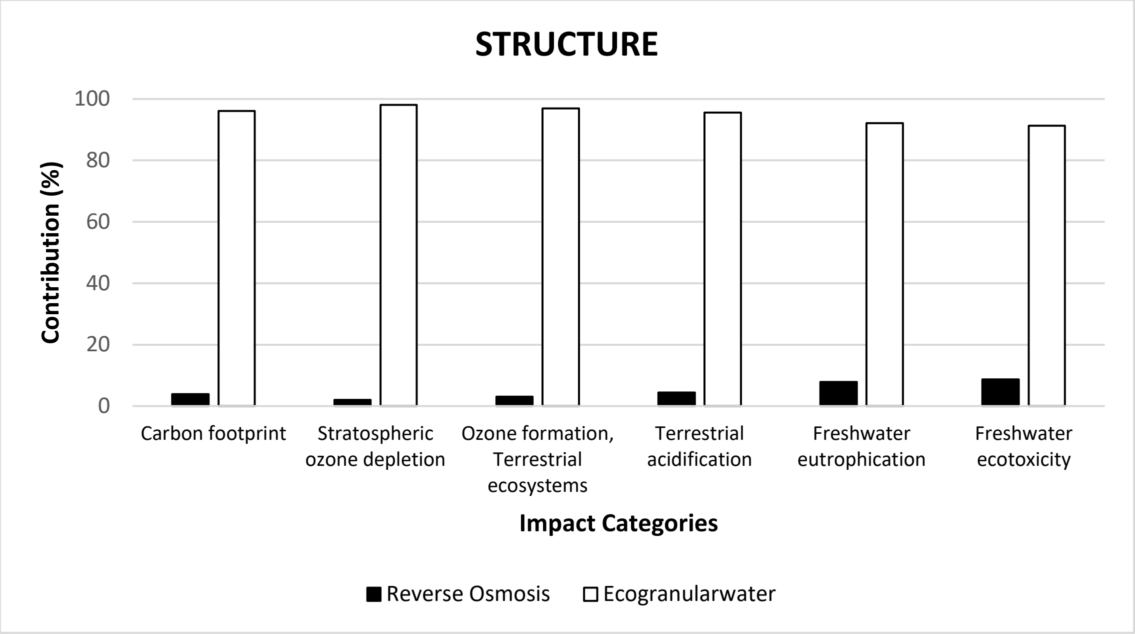

Fig. 3. Contributions of the two technologies to selected impact categories for the structure phase

3.2. ECONOMIC IMPACT ASSESSMENT

The first stage of this assessment entailed estimating the financial costs associated with the production of 1 m^3 of water with the two technologies (Table 11). The EGW technology required more human resources, implying higher staff costs. However, it had lower energy consumption and lower costs for reagents. Additionally, there was no cost associated with the use of membranes. Taken together, the financial costs of producing 1 m^3 of water were 30% lower than the costs of producing the same volume with RO.

Table 11. Operating costs associated with the production of 1 m^3 of water.

Items	**€/m³**		**Percentage structure (%)**	
	RO	**EGW**	**RO**	**EGW**
Staff	0.0893	0.2228	7.69	27.45
Energy	0.3856	0.0701	33.19	8.64
Chemicals	0.4231	0.3675	36.41	45.28
Membranes	0.1117	0.0000	9.61	0.00
EAC of the treatment plant	0.1522	0.1512	13.10	18.63
TOTAL	1.1619	0.8116	100.00	100.00

EAC: Equivalent Annual Cost

In a second stage, the environmental and resource costs were incorporated into the analysis (Table 12). As mentioned above, these concepts reflect the costs due to the raw water rejected in the production process. In the case of the EGW technology, the volume of reject water was negligible and had no environmental impact. However, the high percentage of reject water in RO means substantial environmental and opportunity costs, widening the differential in the cost of producing 1 m^3 of water with the two technologies. Following the indications of the Water Framework Directive, the cost of producing 1 m^3 of water was estimated as 43% lower with the EGW technology than with RO.

Table 12. Operating costs and structure costs associated with the production of 1 m^3 of water.

Items	**€/m^3**		**Percentage structure (%)**	
	RO	**EGW**	**RO**	**EGW**
Staff	0.0893	0.2228	6.20	27.15
Energy	0.3856	0.0701	26.78	8.54
Chemicals	0.4231	0.3675	29.39	44.78
Membranes	0.1117	0.0000	7.76	0.00
EAC of the treatment plant	0.1522	0.1512	10.57	18.43
Opportunity cost	0.1464	0.0009	10.17	1.10
Environmental costs	0.1315	0.0000	9.13	0.00
TOTAL	1.4398	0.8206	100.00	100.00

EAC: Equivalent Annual Cost

4. DISCUSSION

Different physical, chemical and biological water treatment technologies have been developed to solve the problem of groundwater contamination. Notable examples of physical and chemical systems include adsorbent material systems (Awual et al., 2015; Awual, 2019; Awual et al., 2019), electrodialysis (Martínez et al., 2017) and reverse osmosis (Epsztein et al., 2015). Biological treatments include submerged biofilters (Zeng et al., 2019) and aerobic granular systems. These granular systems do not require any type of support on which to develop the biomass, as the granules are made up solely of biomass (Hurtado-Martínez et al., 2021b).

This biological technology was selected for the pilot due to its specific characteristics: it is an inexpensive technology, easy to implement in small municipalities and environmentally friendly.

4.1. ENVIRONMENTAL IMPACT ASSESSMENT

The EGW technology had lower environmental impacts per m^3 than RO in all impact categories. Specifically, the carbon footprint, stratospheric ozone depletion, ozone formation, acidification, eutrophication and ecotoxicity impact categories were lower by 39%, 31%, 44%, 51%, 52% and 59%, respectively. The results showed that the highest environmental impacts with the RO technology occurred in the water treatment phase (Table 9) due to energy consumption in this phase (Table 1). Our results are in accordance with those of Muñoz and Rodríguez Fernández-Alba (2008), Vince et al. (2008), Qiu and Davies (2011), Tarnacki et al. (2011), Zhou et al. (2011)

and Lawler et al. (2015). Ortiz et al. (2007) concluded that replacing fossil fuels with renewable energy will substantially reduce the environmental load. Achieving a shift in the Spanish energy mix toward more renewable energies and certified high quality electricity supply may be one way of reducing the environmental impact of water treatment plants (Vince et al., 2008; Meneses et al., 2010). Tarnacki et al. (2011) highlighted the need for research on energy efficiency, use of renewable energy sources or use of waste heat. The water treatment phase in the EGW technology produced high impacts in the carbon footprint, stratospheric ozone depletion and ozone formation categories due to the inorganic and organic chemical compounds added in this phase (Table 6); therefore, other chemicals should be tested to find ones that generate smaller environmental impacts.

The water treatment phase was far more important than the structure phase in RO, with the former accounting for 99.9% of the impact in all categories, while EGW registered values of 98% in most categories. Similar results were found by Raluy et al. (2005) and Muñoz and Rodríguez Fernández-Alba (2008), who concluded that the operational phase of water production in desalination plants was responsible for 98-99% and 96-99%, respectively, of the overall life cycle impact. Likewise, Bonton et al. (2012) indicated that the impacts of the operational phase were 3 to 9 times greater than those of the construction phase. Therefore, the main contribution to the overall environmental impact of RO and EGW technologies came from the water treatment (Table 9), while the structure phase had an almost negligible impact in comparison. This finding is in line with Friedrich (2001) and Raluy et al. (2005), who reported minor impacts in the construction phase, with values of less than 5% and 15%, respectively.

EGW technology contributed more than RO in the structure phase for all impact categories (Figure 3). This was due to the greater weight of the frame, requiring more materials, mainly in the biological reactors (Table 3). Therefore, recycled materials and/or materials with a longer useful life (mainly for plastic materials) should be employed in the structure.

4.2. ECONOMIC IMPACT ASSESSMENT

It was estimated that to meet the cost recovery objective, rates would have to rise by 60% (Alguacil-Duarte et al., 2020). A complementary contingent valuation analysis was carried out to estimate the population's willingness to pay to help ensure the financial balance of the service. In the best-case scenario, it was estimated that the population would only accept a 20% increase in the price of water and that the resulting cost recovery rate would be 71%. With the EGW technology, considering only the financial costs (and not the environmental and resource costs, which are not accounted for in the municipal budget), it was estimated that the cost recovery rate would be 85%. In the case of Torre-Cardela, implementing a progressive rate increase while also installing EGW technology for water treatment would enable the town council to get closer to the target of cost recovery.

The scenario under study in the municipality of Torre-Cardela is not an exception in Spain. It is just one of many municipalities with a small population, dealing with a financial deficit in the provision of public water services (García-Rubio and González-Gómez, 2020). To a large extent, this deficit emerged because the town was unable to harness the important economies of scale associated with the industry. But it is also the result of the excessive investment of public funds targeted at modernizing and improving the water service seen since the second half of the 1990s (García-Rubio and González-Gómez, 2020). Many of these investments were made without any consideration that, once the infrastructure had been built, the municipalities would have to cover the costs of the service. Moreover, it should be noted that the resident population has, on average, low purchasing power. They are rural population centres with low average incomes. This combination of factors means that the water service in many municipalities is implicitly subsidized. The income obtained from other budget items ends up financing part of the costs for the water supply service.

5. CONCLUSIONS

The study focused on a standardized and widely used technology, reverse osmosis (RO), and a new biological nitrate removal technology based on aerobic granular sludge, named ecogranularwater (EGW). To compare the two technologies, an environmental impact study was carried out, using the life cycle assessment technique, as well as an economic impact study using a cost-effectiveness analysis. This new biological treatment has been implemented for the first time on an industrial scale through a pilot plant that supplies nitrate-free water to a Spanish municipality.

The RO technology registered higher environmental impacts than the EGW technology in all impact categories, while the cost of producing 1 m^3 of water was lower with the EGW technology. This was because RO requires higher energy use in the water treatment phase than the biological technology does. The use of renewable energy sources could be an effective to reduce the environmental impacts. Efforts to further lessen the environmental impact of the EGW technology should seek to reduce the impact of the structure using recycled materials and/or materials with a longer useful life.

Our study showed that:

- The EGW technology produces drinking water in a more environmentally-friendly, cost-effective way, and with lower energy costs.

- The EGW technology is more appropriate than conventional technologies in rural municipalities with nitrate pollution problems.
- The new biological technology contributes to the transition to a green economy and complies with European legislation regarding drinking water quality.
- The decision-making about the technological innovations needed in drinking water treatments to remove nitrates can be supported by environmental and economic studies.

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