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Environmental and economic assessment of a floating constructed wetland to rehabilitate eutrophicated waterways

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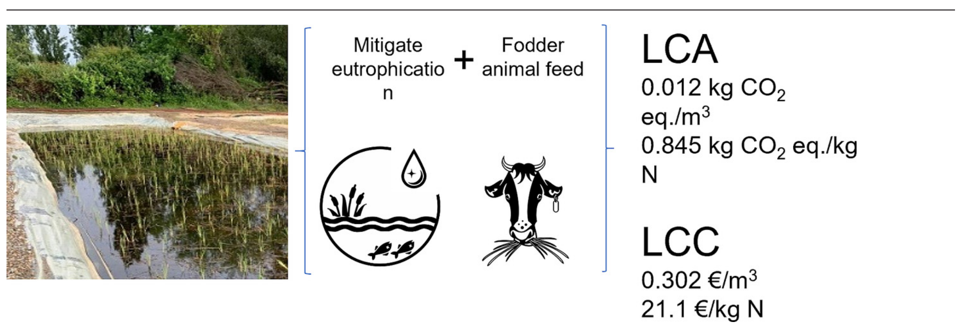
HIGHLIGHTS

- Carbon footprint of floating CW: 0.012 kg CO_2 eq./m^3 or 0.845 kg CO_2 eq./kg N fixed
- Most carbon footprint generated by materials used in the construction stage
- Direct emissions of CH_4 and N_2O need to be evaluated further.
- Economic costs of floating CW amount to 0.302 €/m^3 or 21.1 €/kg of N fixed
- Economic costs lower than small scale wastewater treatment technologies

GRAPHICAL ABSTRACT



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ABSTRACT

While the reduced carbon footprint of conventional constructed wetlands (CW) for wastewater treatment has been described in the literature, far less information is available on the economic performance of floating filters and their application for the treatment of other pressing environmental problems such as freshwater eutrophication. This investigation describes the technical characteristics and the environmental life cycle assessment (*E*-LCA) and a life cycle cost (LCC) analysis of a *Typha domingensis* floating constructed wetland (FCW) designed and constructed to rehabilitate eutrophicated waterways and which also produces biomass for animal feed. The analysis is based on a precise material, energy and economic inventory from a demonstration project built in the Alagón river basin (central Spain). The *E*-LCA followed a cradle-to-grave approach, used the EF3.0 impact assessment methodology and was referred to two complementary functional units related to the water treatment capacity of the floating filter: 1 m^3 of treated water and 1 kg of N fixed, both over a 10-year operating cycle. Climate change emissions were estimated at 0.012 kg CO_2 eq./m^3, which included 0.082 kg CO_2 eq./m^3 caused by the construction, operation and decommissioning of the infrastructure, minus 0.070 kg CO_2 eq./m^3 credits from the production of fodder for animal feed. Considering its nitrogen uptake capacity, this may be represented as 0.845 kg CO_2 eq./kg N. Most of this carbon footprint comes from the construction (63.2 %) and the operation (31.1 %) stages, with the former being dominated by auxiliary materials (mainly plastics and cereal straw) needed to build the infrastructure and the energy system (mainly

Abbreviations: BOD_5, Biological oxygen demand (5 days); CAPEX, Capital expenditure; CH_4, Methane; CF, Carbon footprint; COD, Chemical oxygen demand; CO_2, Carbon dioxide; CV, Coefficient of variation; CW, Constructed wetland; DMB, Dry matter basis; EC, European Commission; EF, Environmental Footprint; E-LCA, Environmental - life cycle assessment; EoL, End-of-Life; Eq, Equivalent; FCW, Floating constructed wetlands; FMB, Fresh matter basis; FU, Functional unit; GHG, Greenhouse gases; GWP, Global warming potential; IPCC, Intergovernmental Panel on Climate Change; ISO, International Organization for Standardization; LCA, Life cycle assessment; LCC, Life cycle cost; LCI, Life cycle inventory; LCIA, Life cycle impact assessment; LULUC, land use and land use change; M&C, Materials and construction; N_2O, nitrous oxide; NMVOC, Non-methane volatile organic compounds; NPV, Net present value; O&M, Operation and management; OPEX, Operating expenditure; Per, person; Per - h, person multiplied by hour; PP, Polypropylene; ppm, parts per million (mg/l); PV, Photovoltaic; PVC, Polyvinyl chloride; SD, Standard deviation; SFW, Surface flow wetlands; SSFW, Subsurface flow wetlands; TOC, Total organic carbon; UPM, Universidad Politécnica de Madrid; VAT, Value added tax.

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PV panels). This same pattern is replicated in most other environmental categories and the aggregated single score. Further research is needed to quantify with precision direct CH_4 and N_2O emissions produced during the operation stage, whose contribution can be significant (up to 64.8 % over indirect LCA emissions). The LCC analysis resulted in discounted expenses over the 10-year cycle of 44,083 € and revenues derived from the sale of fodder for animal feed of 11,429 €, resulting in a net present value of 32,654 €. These expenses may be represented as 0.302 €/m^3 of treated water (or 21.1 €/kg of N fixed). The monetary cost and environmental footprint per functional unit of floating CW are lower than those reported for other conventional small-scale wastewater treatment technologies.

1. Introduction

Water quality and availability is a major global issue, both in terms of its impact on human health and the environment (UNESCO, 2021). One of the most significant concerns relates to eutrophication, a condition caused by the release of minerals and nutrients (primarily nitrogen and phosphorus) into water bodies. This situation leads to excessive growth of aquatic plants and algae whose biological activity increases the presence of organic matter in the water, reduce dissolved oxygen (hypoxia) and may lead to the release of toxins, thereby threatening the healthy functioning of the aquatic ecosystem. Eutrophication is associated with certain human activities, such as the use of fertilisers in intensive agriculture, livestock farming and the release of municipal residues and wastewaters (Farley, 2012). While the best solution to eutrophication lies in the management of the practices that cause the release of such nutrients, in certain cases it may be necessary to resort to the use of abatement technologies that reduce pollutant loads already present in natural or artificial water bodies (Xia et al., 2020). One of these technologies is constructed wetlands (CW), a form of extensive artificial infrastructures designed to replicate the physical, chemical and biological processes that occur in natural wetlands to remove organics, nutrients and other pollutants (Garcia-Serrano and Corzo-Hernandez, 2008; Masi et al., 2018; Verma and Suthar, 2018; Vymazal, 2014). CW are characterised by their simple and chemical-free operation, low energy requirements, reduced operating and investment costs, and optimum integration into the natural environment (Hsu et al., 2011).

Depending on the water circulation pattern, most CW fall into one of two categories (Wu et al., 2015). In surface flow wetlands (SFW) (also referred to as free water surface wetlands), the water flows above ground over the media substrate, typically a native soil that is impervious to water penetration, and through the stems of aquatic plant vegetation. Subsurface flow wetlands (SSFW) are designed in such a way that water level is below the top of the media substrate, thus minimizing human and ecological exposure. In this latter case, water floods the interstitial spaces of the filter bed (gravel of rock), flowing below the soil surface either horizontally (HSSFW) or vertically (VSSFW) (García et al., 2005). The design, operation and purification capacity of these systems has been described in several publications and reviews (García et al., 2010; Ingrao et al., 2020; Kataki et al., 2021b; Kataki et al., 2021a; Wu et al., 2015).

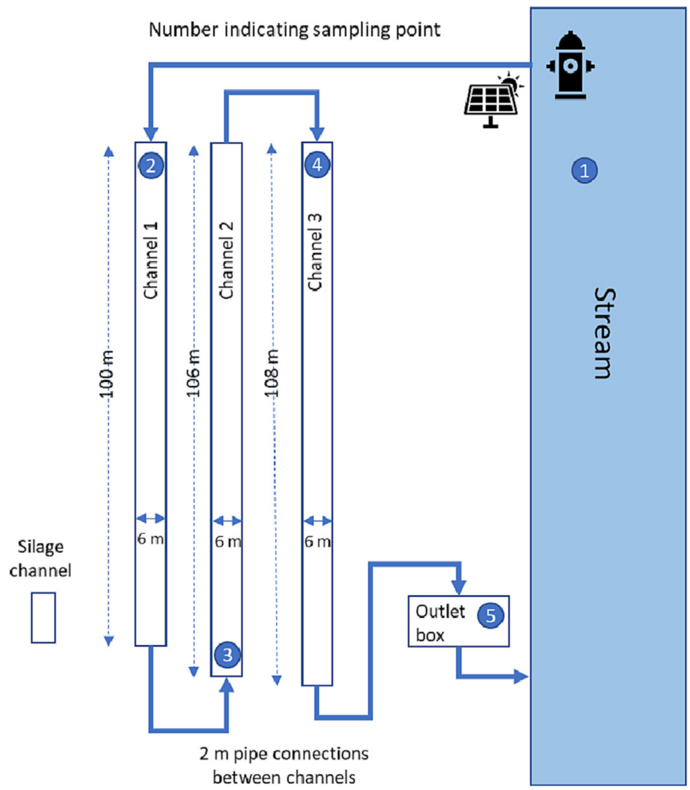
A less explored type of CW are floating constructed wetlands (FCW), also referred to in the literature as floating wetlands or floating filters. This type of hydroponic system benefits from its ability to move up and down depending on water levels (Colares et al., 2020; Pavlineri et al., 2017), which facilitates the development of a submerged rhizome that improves the efficiency and capacity of the system to remove pollutants (Lucke et al., 2019; Melgar-Lalanne et al., 2017; Perdan et al., 2017). The effectiveness of FCW for the treatment of effluents (West et al., 2017; Xia et al., 2019) and to reduce pollutant loads in rivers and ponds (Jones et al., 2017; Olguín et al., 2017) has already been described in the literature.

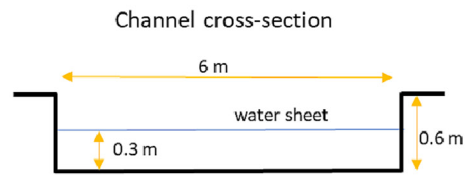
In recent years, a number of investigations have been carried out aimed at evaluating the environmental sustainability of CWs. Most of them used a life cycle approach to quantify the carbon footprint of surface and subsurface CW operating in different natural settings (Bhatt et al., 2019; Cao et al., 2021; Corbella et al., 2017; Forchino et al., 2017; Lutterbeck et al., 2017; Resende et al., 2019a). A meta-analysis review of these publications reports disparate results ranging from 0.055 to 5.3 kg CO_2 eq./m^3 of treated water (Li et al., 2021). This disparity is associated with the characteristics of the CW under consideration, but also with the methodology and scope of the *E*-LCA, which in some cases does not take into consideration direct emissions in the form of CH_4 and N_2O caused by the transformation of organic matter and nitrogenated compounds present in the treated water. These greenhouse gas (GHG) emissions have been reported to be highly variable and site- and time-specific, being strongly affected by the design and operating conditions of the CW system (depth, macrophyte type and density, biological activity, retention time, flow type - surface, subsurface, floating, etc.), environmental conditions (soil type, temperature, etc.) and the characteristics of the treated water (organic matter and nutrient content, salinity, flow rate, etc.) (Mander et al., 2014; Mitsch and Mander, 2018). Experimental investigations also describe how certain types of CWs may work as carbon sinks, a condition that is favoured by the formation of peat and the capping of clay and sandy soils where the CW is settled (Harpenslager et al., 2018). Despite these disparities, comparative *E*-LCA studies describe how CW generate significantly lower impacts (between 2 and 40 times lower, depending on the environmental category) than conventional intensive technologies (e.g., activated sludge) per unit of water treated, mainly due to the consumption of electricity and chemicals, and also the direct emissions incurred during the operation and management of sludge (Garfí et al., 2017; Novoa et al., 2019).

The economic sustainability of a wastewater treatment plant rests on its economic costs per FU, which may be calculated using life cycle cost (LCC) analysis (Swarr et al., 2011). The economic viability of artificial wetlands for wastewater treatment is described in several research papers (Ilyas et al., 2021; Resende et al., 2019a), which report values in the range between 0.45 and 2.50 $€_{2021}/m^3$ of treated water, most coming from capital costs required to build the infrastructures and, to a much lesser extent, operating costs. Comparative analyses describe these costs as being 2–3 times lower than conventional intensive technologies (Flores et al., 2020; Garfí et al., 2017). These low costs, coupled with the need for large areas of land, make these technologies particularly suitable for rural areas and developing countries where land tends to be both inexpensive and widely available (Gallego-Schmid and Tarpani, 2019; Liu et al., 2015).

Most of the information outlined in this introduction refer to conventional constructed wetlands (either SFW or SSFW) utilized primarily for the treatment of municipal wastewaters and also industrial effluents of different types (e.g., textile and food industry) (Flores et al., 2020; Riggio et al., 2018; Saeed et al., 2018). However, much less information is available about the technical features associated with the construction and operation of floating filters, their environmental performance in a broad sense (beyond its carbon footprint), economic viability and the application of this extensive water treatment technology to other pressing environmental problems such as freshwater eutrophication.

Therefore, the main objective of this work was to evaluate the environmental and economic performance of an FCW based on *Typha domingensis* for the treatment of a natural stream impaired by freshwater eutrophication. The study also addresses the additional functionality of the filter in the production of biomass for animal feed. This investigation utilized as primary data a complete material, energy and monetary inventory obtained from a demonstration project built and operated in the Alagón river basin (central Spain). Specific objectives include: i) compilation of a complete material, energy and monetary inventory associated with the construction, operation and end-of-life of the floating filter; ii) identification of life cycle stages and processes contributing the most to the environmental impacts





	Channel				Water			
	Width	Length	Depth	Vol.	Depth	Vol.	Vol. (except roots)	Surface of water sheet
	m	m	m	m3	m	m3	m3	m2
Channel 1	6	100	0.6	360	0.3	180	90	600
Channel 2	6	106	0.6	382	0.3	190.8	95.4	636
Channel 3	6	108	0.6	389	0.3	194.4	97.2	648
TOTAL, channels		314		1130		565.2	282.6	1884
Outlet chamber	1	1.5	0.6	0.9				
Silage channel	4	10	1	40				

Fig. 1. Structure and dimensions of the *Typha domingensis* floating constructed wetland.

and economic costs of the system; iii) identification of environmental impact categories most severely affected; and iv) quantification of economic and environmental benefits associated with using the biomass generated in the FCW for animal feed.

2. Methodology

The Environmental Life Cycle Assessment (*E*-LCA) and the Life Cycle Cost (LCC) analysis of this FCW have been carried out in accordance with the framework set out by the International Standard Organization ISO 14040/14044 (ISO, 2006a, 2006b) and following the guidelines established by the United Nations Life Cycle Initiative (Swarr et al., 2011). Methodological aspects regarding the application of *E*-LCA and LCC are further discussed below.

2.1. Goal definition

The main objective of this study was to evaluate the environmental and economic sustainability of a FCW designed and built to rehabilitate eutrophicated waterways and including its additional functionality in the production of biomass for animal feeding. The analyses were carried out using a life cycle approach and were based on a detailed material, energy and economic inventory generated in a demonstration project.

2.2. Scope definition

2.2.1. System description

The system under investigation is a floating filter of *Typha domingensis* designed by the Agroenergy (GA) Research Group of the Universidad Politécnica de Madrid (UPM) in a demonstration project funded by the European Regional Development Fund (ERDF). The filter was built on the Alagón river basin in 2019 and operated until 2022, using the runoff water collected from a small stream, as it flows through the municipality of Valdeobispo (Cáceres, central Spain). Livestock activity in this area (mainly beef cattle farming) and run-off water from fodder production are responsible for the eutrophication of the river where the floating CW was located. Fig. 1 shows the structure and dimensions of the filter, which consists of three main channels of 100, 106 and 108 m length and 6 m width (1884 m^2). The channels are 0.6 m deep with the height of the water sheet situated 30 cm from the bottom, resulting in a total volume of 565 m^3. It is assumed that 50 % of this volume is occupied by roots and rhizomes during the mature stage of the filter. The water enters the filter from the runoff water stream assisted by a 0.75 kW electric pump connected to a 1.5 kW ground-mounted photovoltaic (PV) system. Polyvinyl chloride (PVC) pipes are used to connect these channels, through which water moves by plug-flow. Channel 3 is connected to an outlet chamber containing a flowmeter where water is homogenised before discharge into the stream. Beside the filter is a smaller channel designed to facilitate the ensiling of biomass.

Fig. 2 show some pictures of different stages in the process of construction, maturation and exploitation of the floating filter. As explained in more detail below, once the civil works have been completed and the auxiliary elements installed (pipes, protection plastic films, energy system, etc.), a substrate bed of 8,000 kg of cereal straw was built on which the *Typha domingensis* seedlings are placed. This structure rises when the channels are flooded with water, facilitating the progressive growth of macrophytes and the development of both their aerial and submerged parts.

Table 1 shows the operating parameters of the filter, with an average daily inflow of 60 m^3/day achieved using a pump operating 12 h per day at 5 m^3/h, resulting in an effective hydraulic retention time of 4.7 days. Average evaporation and evapotranspiration water losses in the floating filter were calculated considering 9 l/m^2 day, which results in 16.93 m^3/day or 28.3 % of the total inlet flow (Stannard et al., 2013). The filter operates 180 days (6 months per year, from May to October), which corresponds to the periods of highest biological activity of the macrophytes and also of highest eutrophication load of the stream. From November to April, the metabolic activity of the plants and microorganisms in the FCW slow down or stop altogether. During this period, the FCW is left in place and no biomass extraction is necessary. Nitrogen fixation during this dormant phase is assumed to be minimal or non-existent, although other related

Fig. 2. Different stages in the process of construction, maturation and exploitation of the *Typha domingensis* floating constructed wetland (numbers indicate the channels). Photographs courtesy of Mr. César Martín (Viveros La Dehesa S.L.).

processes, such as denitrification, may continue to occur at a reduced rate. Nevertheless, due to its small contribution, the scrubbing activity of the filter during the dormant period has not been considered in the analysis.

The analysis covers a 10-year cycle, after which the floating filter needs a complete overhaul which includes replacing auxiliary components (geotextiles and plastics) and replanting of macrophyte seedlings. Due to their longer estimated lifetimes, the economic costs and environmental burdens of the civil works (40 years) and energy system (20 years) were allocated over 4 or 2 successive 10-year cycles, respectively.

Table 1
Typha domingensis floating constructed wetland design parameters.

Inlet flow rate	60.00	m^3/day
Daily operating time	12.00	h/day
Hourly operating flow rate	5.00	m^3/h
Average evapotranspiration losses	17.0	m^3/day
Outflow rate	43.0	m^3/day
Hydraulic retention time	4.71	day
The filter operates May–October (spring and summer)	180	days/year
Average life span	10	years
Volume of water treated/year	10,800	m^3/year
Volume of treated water/lifetime	108,000	m^3/lifetime

2.2.1.1. Biomass production. The nitrogen removal capacity of the filter is directly related to its biomass production capacity. Table 2 illustrates this production capacity over a 10-year cycle, which has been calculated considering experimental values obtained during the first three years of filter establishment and operation, and by extrapolating these values to later times using expert judgement from longer-established floating filters built and operated by the research team (Fernández and Doménech, 2017). Estimations were based on a yearly dry matter basis (DMB) biomass yields of 1.89 kg DMB/m^2 and 3.08 kg DMB/m^2 for aerial and submerged biomass, respectively, and an effective surface area of the floating filter of 1,884 m^2. The average moisture content for the fresh aerial and submerged biomass was 85 wt% and 90 wt%, respectively. These values of biomass production by floating CW are in line with those reported by other researchers (Olguín et al., 2017; Saeed et al., 2016).

As shown in Table 2, the floating filter is only harvested once in the first year (year zero), to ensure effective rooting of the macrophytes, yielding 3,561 kg DMB of biomass (equivalent to 23,738 kg of fresh biomass). In

Table 2
Average biomass productivity per cycle (dry matter basis).

	Year			
	0	1	2–8	9
Number of harvesting cycles				
Aerial biomass	1	2	2	2
Submerged biomass	0	0	0	1
Aerial biomass				
Annual yield (kg)	3,561	5,697	5,697	5,697
Annual extraction (kg)	3,561	5,697	5,697	5,697
Remaining after harvest (kg)	0	0	0	0
N uptake (kg)	89.0	142.4	142.4	142.4
Submerged biomass				
Annual growth (kg)	5,793	2,897	0	0
Annual extraction (kg)	0	0	0	8,690
Remaining after harvest (kg)	5,793	8,690	8,690	0
N uptake (kg)	115.9	57.9	0	0
Silage biomass				
Total silage biomass output (kg dry matter)	3,091	4,693	4,693	11,210
Total silage biomass income (€)[a]	773 €	1,173 €	1,173 €	2,803 €

[a] Undiscounted.

Table 3
Representative operating conditions of the floating constructed wetland: water treatment and nitrogen removal capacity in three representative annual scenarios.

Year		0	1	Successive
Inflow rate	m^3/day	60.0	60.0	60.0
Outflow rate	m^3/day	43.0	43.0	43.0
Evapotranspiration	m^3/day	17.0	17.0	17.0
Influent N concentration (C_0)	mg/l	20.0	20.0	20.0
Effluent N concentration (effective)	mg/l	1.43	2.02	9.50
Effluent N concentration (theoretical) (C_1)[a]	mg/l	1.03	1.45	6.81
Average mass N removal	kg/day	1.14	1.11	0.70
Average mass N removal	kg/year	204.9	200.4	142.4
Reduction (wt%)		94.9 %	92.8 %	65.9 %
k_A		0.0945	0.0836	0.0343

[a] Assuming no water losses, for the calculation of operating constants (k_A) in Eq. (1).

the following 9 years, two harvests are carried out annually resulting in a 20 % reduction in biomass yield per collection. During this period of filter maturity, 5697 kg DMB of biomass per year are collected (equivalent to 37,981 kg of fresh biomass). The submerged biomass grows during the first two years to a maximum of 8,690 kg DMB, a value that remains constant during the following years, meaning no additional nitrogen fixing capacity. In the last annuity of the 10-year cycle (year nine), both the aerial and the submerged biomass are harvested in preparation for a complete overhaul of the floating filter, totalling a production of 14,387 kg DMB of Typha (equivalent to 124,881 kg of fresh biomass).

The silage process yields 86.8 wt% of the original biomass, with the remaining 13.2 wt% representing fermentation losses. The market price of this silage biomass for use as fodder for animal feed is very variable depending on the demand and supply of alternative animal feeds, which are in turn affected by weather conditions, local livestock and agricultural practices, international feed and animal husbandry markets, etc. Standard market prices reported for Mediterranean countries between 2010 and 2020 typically range between 225 and 300 $€_{2021}$/t (DMB), although these prices have increased significantly in 2021 and 2022 up to 350–400 $€_{2021}$/t due to the global energy and raw materials crisis (MCC, 2023). For the purpose of this investigation, a conservative average price of 250 $€_{2021}$/t (DMB) for the silage biomass was assumed, resulting in undiscounted annual incomes of 773 $€_{2021}$ in the first year, 1,173 $€_{2021}$ during the maturity stage and 2,803 $€_{2021}$ in the last annuity of the 10-year operating cycle.

2.2.1.2. Nitrogen removal capacity. The water purification capacity of the floating filter has been calculated considering the biomass yields and the nitrogen (N) content of the aerial (2.5 wt%) and submerged (2.0 wt%) biomass fractions. Previous research on the ability of floating *Typha domingensis* filters to remove N and P from runoff waters had described that these nutrients accumulated mainly in plant tissues and not in the sediment (Di Luca et al., 2019). As shown in Table 2, the nitrogen removal capacity of the filter was maximized in the first (89 + 115.9 = 204.9 kg) and second (142.4 + 57.9 = 200.3 kg) years of operation, due to the development of both the aerial and the submerged biomass fractions. A plateau is reached at 142.4 kg/year in subsequent years when the submerged biomass attained a steady state situation and two harvests were made every year. These values of nitrogen uptake by floating CW are in line with those reported by other researchers (Barco and Borin, 2017; Pavlineri et al., 2017).

Table 3 describes the water treatment capacity of the filter in different annuities assuming the standard inflow conditions of 60 m^3/day, 20 ppm total nitrogen and 28.3 % evapotranspiration loses. Considering the seasonal operation of the filter (180 days between May and October), this leads to a daily N removal capacity of 1.11–1.14 kg of N/day for the first two years of the cycle (equivalent to 200.4–204.9 kg/year) and 0.70 kg of N/day (equivalent to 142.4 kg/year) during successive annuities. The lower N uptake capacity during the maturity stage of the filter is caused by the stabilization of the submerged fraction after the second year of operation, while the aerial fraction maintains its N fixation capacity throughout the entire 10-year cycle. This means average N removal capacities between 93 and 95 wt% in the first two years and 66 wt% thereafter, to produce effective effluent concentrations between 1.43 and 2.02 ppm in the first two years and 9.50 ppm thereafter. This purification capacity would be sufficient to meet the European regulatory limits for nitrogen discharges into sensitive (10 ppm) watercourses (Directive 91/271/EEC).

Table 3 also shows the reaction rate constant (kA) for the floating filter following the removal model by (Brix, 1994) based on first-order plug-flow kinetics (see eq. 1). This constant can be used to design and define N uptake in CW of different scale and layout. The results describe the evolution of ka (which describes the N removal capacity) at different stages of the biological activity of the filter, with higher values (k_A up to 0.095) in the development stage (indicating a higher cleaning capacity) and lower values (k_A = 0.034) in the maturity stage. These values compare favourably with those published by (Garcia-Serrano and Corzo-Hernandez, 2008) for N removal in SCW (k_A = 0.036).

$$k_A = \frac{Q}{S}\ \ln\left[\frac{C_0}{C_1}\right] \tag{1}$$

k_A = first order constant for N scrubbing (m/day)
Q = inflow to the treatment system (m_3/day)
S = filter surface area (m^2)
C_o = inlet concentration (mg/l)
C_1 = outlet concentration (mg/l) assuming no water losses

2.2.2. System functionality, multifunctionality and functional unit (FU)

The main FU used in the environmental and economic LCAs was the treatment of 1 m^3 of water over the 10-year operating cycle considered. In addition, a secondary FU was used focusing on its N cleansing capacity and was defined as the removal of 1 kg of nitrogen. A direct relationship between these two parameters can be determined for the floating filter considering that the system treats 108,000 m^3 of water and fixes 1545 kg of nitrogen over a 10-year operating cycle, resulting in 14.3 g of nitrogen removed per m^3 of treated water.

The floating filter evaluated in this investigation is a multifunctional system. Its primary purpose relates to its capacity to remove N from an eutrophicated stream and its secondary function to the production of *Typha domingensis* biomass, which is then ensiled to produce fodder for animal feed. According to the requirements of ISO 14040 (ISO, 2006a, 2006b) this secondary function was incorporated into the analysis using a system expansion approach which considered the environmental credits associated with the substitution of an organic grass silage sourced from the commercial database Ecoinvent 3.8 (Grass silage, organic {CH}| production | Cut-off,

U) (Wernet et al., 2016). This system expansion was analysed as an independent stage in the life cycle of the floating filter.

The environmental allocation in the LCA of components with a service life longer than the 10-year cycle considered in this analysis (40 years for civil works and 20 years for energy system) was made considering a constant emission distribution over their operation time. The economic allocation in the LCC assumed a residual value for these components at the end of the 10-year cycle equivalent to one fourth and one half of their total worth, respectively.

2.2.3. System boundaries and cut-off criteria

The transport stage relates to the transportation of raw materials, equipment and machinery required to build the floating filter, from their point of distribution to the construction site. The operation and management (O&M) stage considers material, energy and economic flows associated with the functioning, maintenance works and biomass extraction and silage activities. This stage does not account for the uptake and direct emission of biogenic carbon, assuming that shallow depth and water movement inhibit anaerobic digestion processes, while short-cycle biogenic CO_2 flows do not contribute to climate change (Mander et al., 2014). The end-of-life (EoL) stage considers the management of materials (plastics) and equipment (pumps, PV systems, etc.) at the end of their useful lives. This EoL was analysed considering the waste management rates reported by the Ministry for Ecological Transition and Demographic Challenge (MITECO, 2019).

Table 4 describes the life cycle stages and processes considered in the *E*-LCA and LCC analysis of the floating filter. The Materials and Construction (M&C) stage includes processes related to the extraction and production of materials and components, and the construction of the infrastructures. In the economic analysis, this M&C stage is associated with the capital expenditures (CAPEX) incurred during project construction, as opposed to the operation and management (O&M) stage which is associated with operating expenditures (OPEX). The transport stage relates to the transportation of raw materials, equipment and machinery required to build the floating filter, from their point of distribution to the construction site. The operation and management (O&M) stage considers material, energy and economic flows associated with the functioning, maintenance works and biomass extraction and silage activities. This stage does not account for the uptake and direct emission of biogenic carbon, assuming that shallow depth and water movement inhibit anaerobic digestion processes, while short-cycle biogenic CO_2 flows do not contribute to climate change (Mander et al., 2014). The end-of-life (EoL) stage considers the management of materials (plastics) and equipment (pumps, PV systems, etc.) at the end of their useful lives. This EoL was analysed considering the waste management rates reported by the Ministry for Ecological Transition and Demographic Challenge (MITECO, 2019).

Table 4
Stages and processes considered in the life cycle of the floating filter.

Materials and construction	• Land transformation • Civil works for main channels, silage channel and outlet box • PVC connection pipes • Pumps and energy system, including PV panels, support structure, inverter and electricity system. • Weed-proof plastic mesh • Plastic film cover • Cereal straw substrate • Seedling production (nursery)
Transport	• Transport of materials, equipment and machinery • Transport of materials, equipment and machinery from the distribution point to the filter
Operation and management	• Land occupation • General maintenance of premises and constructed wetlands • Technical maintenance for more sophisticated repairs • Mechanised harvesting of aerial and submerged biomass (including transport of machinery) • Biomass silage • System monitoring
End of life	• Transport of materials to waste processing facility • Waste sorting and processing • Recycling and energy valorisation • Landfill disposal of non-recoverable fraction

The cut-off criteria for unit processes employed in this LCA was set at 1 % of its total mass and energy input and 5 % per life cycle stage. This cut-off criteria does not apply to products classified as hazardous or that may cause significant impacts during extraction, transformation, use or disposal. Based on this, the LCA has left outside the system boundaries the economic costs and environmental burdens associated with the design and administrative management of the floating filter, the transport of personnel to their workplace and the transport of raw materials from their point of origin to the distribution outlet.

2.2.4. Environmental impact categories and assessment methodology

The E-LCA focused primarily on the climate change category, which was quantified considering the global warming potential (GWP) over 100 year using the methodology reported by the Intergovernmental Panel on Climate Change (IPCC) 2013 GWP 100a (IPCC, 2013). For other environmental categories, the EF3.0 (adapted) v1.0 impact assessment method was used, based on the European Commission's Environmental Footprint methodology (Fazio et al., 2018). This method considers 16 impact categories: Climate change; Ozone depletion; Ionising radiation; Photochemical ozone formation; Particulate matter; Human toxicity, non-cancer; Human toxicity, cancer; Acidification; Eutrophication, freshwater; Eutrophication, marine; Eutrophication, terrestrial; Ecotoxicity, freshwater; Land use; Water use; Resource use, fossil; Resource use, minerals and metals. To avoid unintentional bias, indicators associated with these 16 environmental categories were systematically reported. However, for practical reasons, discussion focused on the priority categories of climate change and freshwater eutrophication. Additionally, characterized impacts were aggregated into a single score indicator using the normalizing and weighting factors included in the EF3.0 method (Fazio et al., 2018). While aggregated indicators such as the single score provide a comprehensive view of the environmental performance of the products such as the floating filter, it is essential to recognize that the results are highly uncertain and depend on the normalisation and weighting factors applied in this method, which are subjective and can be influenced by the values and priorities of the parties involved in their development (PRé Consultants, 2016). *E*-LCA modelling was carried out using SimaPro v 9.3, and E-LCA and LCC calculations were carried out in Microsoft Excel.

2.2.5. Economic analysis

The time preference of the economic analysis was based on a real discount rate of 2.5 %, which is deemed appropriate for projects of social and environmental interest (Hunkeler et al., 2008). Unless otherwise stated, all economic values in this publication refer to 2021 euros ($€_{2021}$). Whenever necessary, economic values were updated from their original sources using inflation rates for Spain reported by the European Central Bank (ECB, 2022).

2.2.6. Uncertainty and sensitivity assessment

The robustness of the results has been assessed by means of uncertainty and sensitivity analyses. The investigation focused first on the quality of the background inventory datasets employed to build the LCA models, as reported by Ecoinvent using the Pedigree matrix approach (Weidema and Wesnæs, 1996). Monte Carlo simulations (1000 iterations) were run on the LCA models using the SimaPro software to determine coefficients of variation (CV) and standard deviations (SD) for each of the environmental categories considered in the EF3.0 method. The sensitivity analysis focused on the categories of climate change and monetary costs and was performed for a 50 % variation in the input data of key parameters. Additional analyses were conducted on the effect of certain modelling assumptions (direct emissions and nitrogen scrubbing capacity) on the environmental and economic results of the model.

2.3. Life cycle inventory assessment

This section provides general information about the inventory data used to model the environmental and economic sustainability of the floating filter. A complete description of this inventory is available in the Supplementary Information. As described in Section 2.2.1, this information was compiled using as a reference the demonstration project on the Alagón river basin (central Spain) built in 2019 and operated until 2022 by researchers from Universidad Politécnica de Madrid (UPM) and Universidad de Extremadura (UNEX). Inventory data beyond this three year period were projected according expert judgement from longer-established floating filters built and operated by the research team (Fernández and Doménech, 2017). Generic background life cycle inventories required to model the system were sourced from Ecoinvent 3.8 (Wernet et al., 2016) and the World Food LCA Database (Nemecek et al., 2019).

The analysis assumed that the construction of the floating CW was promoted by local authorities, which were also the owners of the land occupied by the project. Therefore, the economic analysis excludes any corporate taxes, profit margins and financial costs which may apply if the project were a private initiative. Personnel expenses were calculated considering an hourly hiring cost (10–25 €/per-h, depending on technical expertise required). Machinery expenses (30–60 €/h) were calculated considering standard hourly rental costs for a tractor with different implements (including transport of equipment, operator salary, fuel, insurance, etc.). These values are representative for this type of activities in rural areas of central Spain.

2.3.1. Materials and construction stage

The inventory of the materials and construction stage has been structured into the following sections: land transformation, construction of civil infrastructures (including main channels, silage channel and outlet chamber), auxiliary materials, energy system, production of seedlings and transportation of machinery, equipment and auxiliary materials.

The land transformation item includes the transformation of a 3000 m^2 meadow with no previous commercial use. Since constructed wetlands have been reported to promote biodiversity (Semeraro et al., 2015), the transformation of this grassland into a floating filter has been assumed to involve no deterioration of the original environmental quality. Regarding the civil infrastructures, the construction of the main water channels, the silage channel and the outlet box involved the hiring of machinery and personnel for the excavation, movement and preparation of the land, and the consumption of construction materials (cement, bricks, sand, water). Auxiliary materials include the weed-proof polypropylene (PP) plastic mesh and the waterproof PP film used for the lining of channels and adjoining areas. Eight tonnes of barley straw were used to build the bed where the seedlings were inserted. The environmental performance of this straw was modelled considering the production of barley under non-irrigated conditions and an economic allocation approach (Nemecek et al., 2019). The energy system consisted of a hydraulic pump, a PV system (including panels, inverter, ground mounting structure and electric system) and a water flowmeter. Inventory data for the production of seedlings was obtained from a local plant nursery and total demand was calculated considering a plant density of 16 units/m^2. The transport stage was calculated considering a 25 km default distance of dedicated road trips (idle return) from the distribution site to the floating filter using unspecified trucks.

Based on these inventories (see Supplementary Information Table SI 1), the total investment cost of building the floating wetland was estimated at 28,458 €. Most of this initial investment cost (50.8 %) corresponded to the production of the *Typha domingensis* seedlings, followed by the civil works (17.4 %), the energy system (17.4 %) and the auxiliary materials (plastic mesh, film and straw) (14.3 %). It should be noted that the lifetime of each of these elements has an impact on their actual contribution to the net cost of the floating filter, as calculated using LCC.

2.3.2. Operation and management stage

The annual inventory requirements for the O&M stage varies depending on the maturity stage of the floating CW (filter establishment in year 0, filter maturity in years 1–8 and filter removal and dismantling in year 9, which includes extraction of submerged biomass, decommissioning of the filter and EoL management of materials.

The inventory of the materials and construction stage has been structured into the following sections: general and technical maintenance, aerial and submerged biomass extraction, transport of machinery, biomass silage. and decommissioning and end of life. As described in Supplementary Information Table SI 2, the O&M stage includes the occupation of 3000 m^2 of pasture-equivalent land, the consumption of pump lubricating oil and the hiring of unskilled staff over the lifetime of the filter for general maintenance, including small repairs, manual weeding and pest control, etc. A budget was also allocated for more technical actions, including periodic monitoring and water quality sampling. Aerial and submerged biomass extraction required the annual hiring of harvesting machinery and personnel for collection and packaging of silage. This harvesting activity was more intense in year 9, due to the extraction of submerged biomass. Machinery transport requirements considered the same 25 km covered by road.

2.3.3. End of life stage

The EoL stage refers to the renovation of the filter at the end of the 10-year cycle and the management of materials, equipment and infrastructures at the end of their useful lives. This renovation involved the hiring of lighter duty machinery and personnel. Materials (plastics) and components (pumps, PV panels, inverter, mounting structure and electricity system) were assumed to be taken by road to the recycling centre located 10 km from the filter (idle return using unspecified trucks). The equipment were manually disassembled and recoverable parts (metals, cardboard, plastics and glass) sorted and managed according to the ratios reported by the Ministry for Ecological Transition and Demographic Challenge (MITECO, 2019): PP (78 % recycling, 16 % disposal and 6.1 % incineration), PVC (78 % recycling, 22 % disposal), metals, glass, paper and cardboard (100 % recycling). Non-recoverable materials were assumed to be shredded and landfilled. A cut-off approach has been used to model the recyclable fractions where they were not been awarded any environmental credits due to the substitution of primary materials but do not receive any loads from their disposal as a waste.

2.3.4. Direct GHG emissions

Direct GHG emissions were estimated considering the CH_4 and N_2O emission ranges for CWs of different type, as reported by (Mander et al., 2014), and considering their assimilation to the characteristics of the floating filter investigated in this article. Biogenic CO_2 emissions were assumed to make no net contribution to climate change because they operate on a short (< 100 years) carbon cycle (IPCC, 2021). Owing to its aerobic and floating nature, the analysis assumed no carbon sequestration capacity in the floating filter. Direct methane emissions were calculated considering the emission factors ((CH_4-C/inflow TOC_{in}) * 100 %) reported for vertical subsurface (1.28 %), horizontal subsurface (3.8 %) and free water surface (18 %) flow CW, and assuming a total organic content (TOC) of the inflow water of 1–10 ppm, which would be representative of unpolluted natural streams. Direct N_2O emissions were calculated considering the environmental factors ((N_2O-N/inflow TN_{in}) * 100 %) reported for vertical subsurface (0.02 %), horizontal subsurface (0.34 %) and free water surface (0.11 %) flow CW, and assuming an average total nitrogen content of the inflow water of 20 ppm. The analysis took into account the 180 days of annual operation of the floating filter, for an annual treatment capacity of 10,800 m^3/year, and the characterization factors reported in EF3.0 method (adapted) v1.02 for biogenic methane (34 kg CO_2 eq. /kg CH_4 bio) and nitrous oxide (298 kg CO_2 eq. /kg N_2O bio) (Fazio et al., 2018).

3. Results and discussion

3.1. Environmental analysis

3.1.1. Analysis of characterized impacts

Table 5 shows the characterized impacts of the floating filter per volume of treated water. The impact generated on the climate change category along the value chain of the system was calculated to be 0.082 kg CO_2 eq./m^3. Subtracting the credits associated with the production of biomass

Table 5
Characterised environmental impacts and economic costs of the floating filter per volume (m^3) of treated water.

Impact Category	Units	Materials and Construction	Transport Raw Materials	Operation and Management	End of Life	Total (excluding credits)	Credits from fodder	Grand total (including credits)
Climate change	kg CO_2 eq	5.19E-02	1.49E-03	2.55E-02	3.19E-03	8.21E-02	−7.01E-02	1.21E-02
Ozone depletion	kg CFC11 eq	3.23E-09	3.49E-10	2.88E-09	1.14E-10	6.58E-09	−5.80E-09	7.73E−10
Ionising radiation	kBq U-235 eq	1.22E-03	9.95E-05	1.24E-03	3.37E-05	2.59E-03	-1.95E-03	6.45E-04
Photochemical ozone formation	kg NMVOC eq	2.77E-04	9.55E-06	1.08E-04	3.52E-06	3.99E-04	−4.11E-04	−1.15E-05
Particulate matter	disease inc.	3.70E-09	1.64E-10	1.65E-09	5.44E-11	5.58E-09	−2.90E-08	−2.34E-08
Human toxicity, non-cancer	CTUh	2.14E-09	2.09E-11	2.13E-10	3.72E-11	2.41E-09	1.76E-08	2.00E-08
Human toxicity, cancer	CTUh	7.59E-11	7.24E-13	1.23E-11	6.82E-13	8.96E-11	6.81E-11	1.58E-10
Acidification	mol H+ eq	5.08E-04	8.44E-06	1.08E-04	3.12E-06	6.27E-04	−4.31E-03	−3.68E-03
Eutrophication, freshwater	kg P eq	4.75E-06	1.09E-08	3.96E-07	5.77E-09	5.17E-06	−2.46E-05	−1.94E-05
Eutrophication, marine	kg N eq	4.21E-04	3.03E-06	2.87E-05	1.23E-06	4.54E-04	−8.41E-04	−3.88E-04
Eutrophication, terrestrial	mol N eq	1.57E-03	3.34E-05	3.16E-04	1.24E-05	1.94E-03	−1.91E-02	−1.71E-02
Ecotoxicity, freshwater	CTUe	1.53E+00	1.81E-02	1.94E-01	2.07E-02	1.77E+00	−8.88E-01	8.78E-01
Land use	Pt	2.30E+00	1.95E-02	1.37E+01	1.82E-03	1.60E+01	−4.86E+01	−3.26E+01
Water use	m^3 depriv.	8.44E-02	7.52E-05	1.36E-02	1.33E-04	9.82E-02	−8.90E-03	8.93E-02
Resource use, fossil	MJ	7.26E-01	2.29E-02	6.35E-01	8.07E-03	1.39E+00	−6.98E-01	6.94E-01
Resource use, minerals and metals	kg Sb eq	1.90E-06	4.99E-09	1.09E-07	1.20E-09	2.01E-06	−5.04E-07	1.51E-06
Single score	μPt	8.85	0.146	3.787	0.130	12.9	−22.4	−9.46
Life Cycle Costing	€	0.218	–	0.188	0.0031	0.408	−0.106	0.302

for animal feed (0.070 kg CO_2 eq./m^3) results in a grand total of 0.012 kg CO_2 eq./m^3. Ninety eight percent of these emissions are fossil based, 0.17 % biogenic (mainly due to emission of biogenic methane) and 1.82 % related to land use and land use change (LULUC). These emission factors have also been calculated using the nitrogen fixation function of the floating filter as a reference. For this purpose, the water treatment capacity (108,000 m3) and the nitrogen fixation capacity (1,545 kg) of the filter over a 10-year cycle have been considered, resulting in 0.0143 kg of N per m3 of treated water. Based on this, the total carbon footprint per unit mass of fixed N may be expressed as 5.74 kg CO_2 eq./kg N when excluding the production of biomass for animal feed or 0.845 kg CO_2 eq./kg N when these credits are included.

The climate change emissions of the floating filter compared favourably with results for surface and subsurface flow CW published by other authors using a similar *E*-LCA scope (between 0.3 and 1.2 kg CO_2 eq./ m^3 reported by (Flores et al., 2020; Garfí et al., 2017) or the average value reported by (Li et al., 2021) for a meta-analysis of published research (0.48 kg CO_2 eq. /m^3).

Fig. 3 describes the contribution of different life cycle stages and processes to the carbon footprint of the floating filter. The results show that

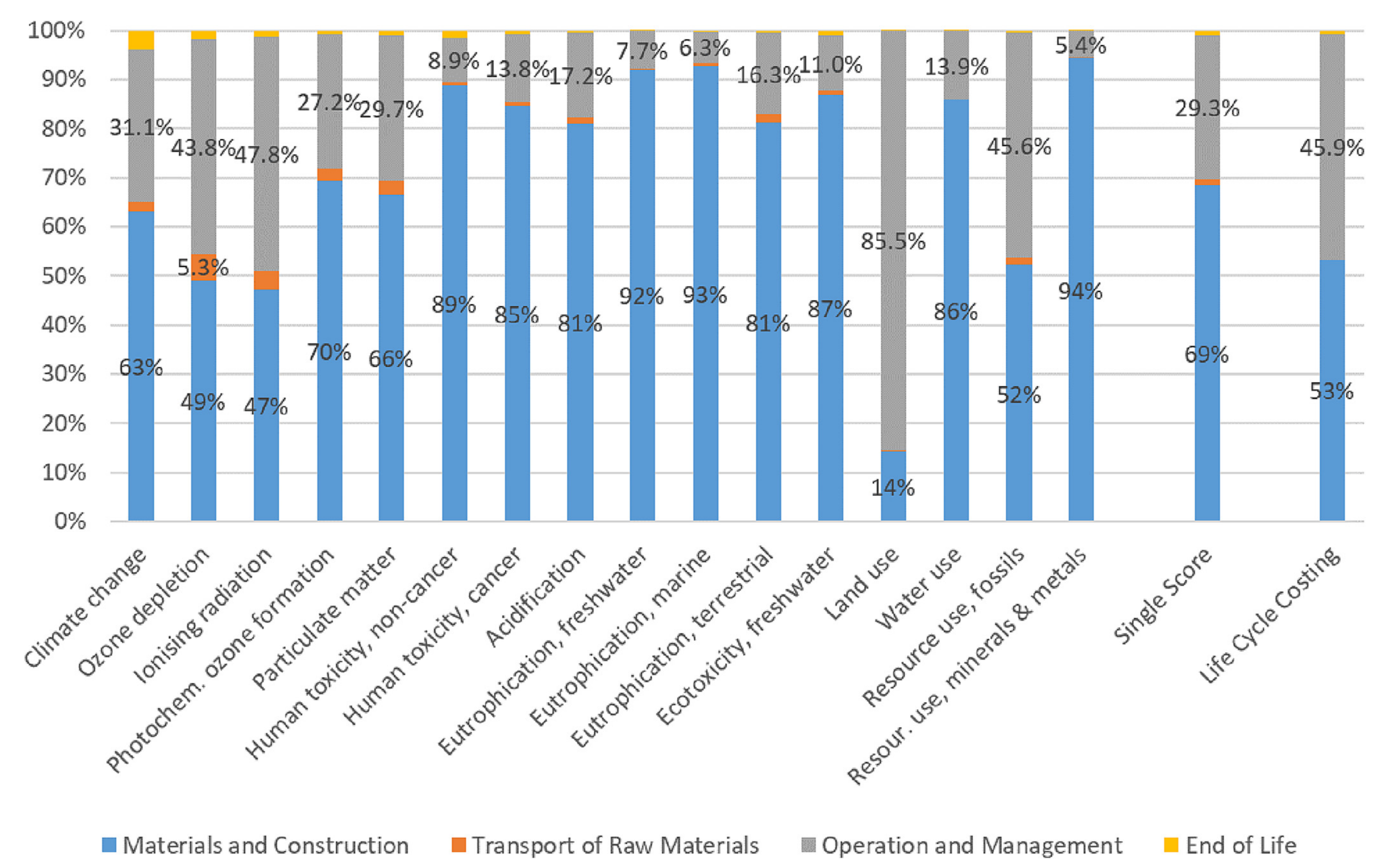


Fig. 3. Contribution of different life cycle stages to total environmental impacts generated by the floating filter (excluding credits from the production of fodder for animal feed).

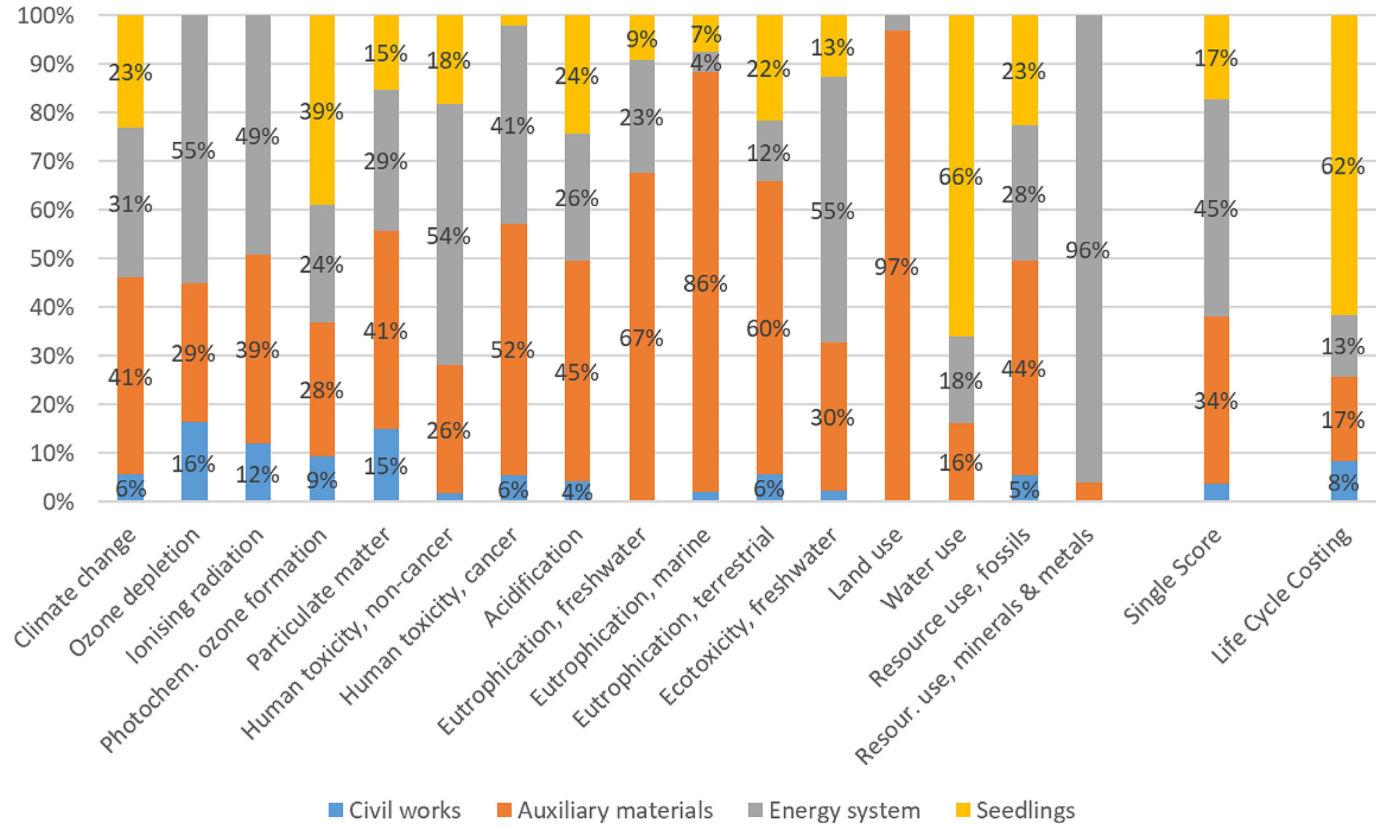


Fig. 4. Life cycle stage contribution to environmental impacts generated by the materials and construction stage of the floating filter.

most these climate change emissions come from the M&C (63 %) and the O&M (31 %) stages, while the contribution of EoL activities (3.9 %) and transport (1.8 %) are very limited. When looking at environmental categories other than climate change, the results show a similar profile where most of the impacts are driven by the M&C life cycle stage. The key exception is the land use indicator, dominated by the O&M stage due to extension (3000 m^2/year) and quality (meadow) of the terrain occupied by the filter. The overall environmental analysis that may be extracted from the single score indicator confirms the dominance of the M&C (68.5 %) and O&M (29.3 %) stages, and the limited contribution of the transport and EoL stages (< 1.1 %).

A process contribution analysis of the M&C stage (see Fig. SI 1 in Supplementary Information) on the climate change category describes a strong contribution of the auxiliary materials and energy system substages (41 % and 31 %, respectively) and comparatively lower inputs from the seedlings and civil works. The results also describe that most of the carbon emissions generated by the energy system corresponds to the fabrication of the PV installation (96 %), in particular the PV panels (70 %), the mounting structure (15 %) and the inverter (8.3 %). Likewise, most of the carbon emissions generated by the auxiliary materials correspond to the barley straw (64 %) followed by the plastic films and geotextiles (36 %).

Fig. 4 illustrates how the dominance of the auxiliary materials in the M&C stage is replicated in most other impact categories besides climate change. For instance, the strong contribution of the auxiliary materials substage in the eutrophication and land use categories are associated with the agricultural activities required to produce the straw utilized to build the floating structure. Key exceptions are human toxicity, ecotoxicity and Resource use, minerals and metals, which are dominated by the energy system due to environmental burdens associated with the fabrication of the PV systems. The holistic perspective provided by the single score shows a dominance of the energy system in the M&C stage (45 %), which is due to its strong presence on impact categories other than climate change, and the normalisation and weighting factors given by the EF3.0 method to these environmental aspects. An in-depth analysis of the O&M process contribution shows that most of the carbon emissions in this stage come from the production of the plastic film (55 %) utilized to silage the biomass, the transport of materials and machinery (24 %) and the machinery used to harvest the biomass (20 %).

3.1.2. Analysis of direct greenhouse gas emissions

The environmental footprints described in the preceding section consider the impacts associated with the construction, operation and end of life of the floating filter, but do not include direct emissions of CH_4 and N_2O, whose contributions are not precisely defined in the literature for floating filters. Table 6 illustrates the range of direct GHG emissions that could be expected from a CW of similar capacity (10,800 m^3/year) and operating at TOC_{in} and TN_{in} of 10 ppm (26 ppm DBO_5) and 20 ppm, respectively, calculated using the emission factors proposed by (Mander et al., 2014) (see Section 2.3.4). This carbon load would be in the upper range for a natural uncontaminated stream while the nitrogen load would be characteristic of an eutrophicated river, for which the floating filter would be intended.

In relation to methane, an average of 3.49E-02 kg CO_2 eq./m^3 could be estimated for the three CW technologies described in Table 6, which would

Table 6
Direct GHG emissions in CW assimilated to the floating filter.

	EF	TOC_{in}	kg CH_4/m^3	kg CO_2 eq./m^3
Free water surface (FWS)	18.00 %	10 ppm	2.40E-03	8.16E-02
Vertical subsurface flow (VSSF)	1.28 %	10 ppm	1.71E-04	5.80E-03
Horizontal subsurface flow (HSSF)	3.80 %	10 ppm	5.07E-04	1.72E-02
	EF	TN_{in}	kg N_2O/m^3	kg CO_2 eq./m^3
Free water surface (FWS)	0.11 %	20 ppm	4.33E-05	1.29E-02
Vertical subsurface flow (VSSF)	0.02 %	20 ppm	7.08E-06	2.11E-03
Horizontal subsurface flow (HSSF)	0.34 %	20 ppm	1.34E-04	3.99E-02

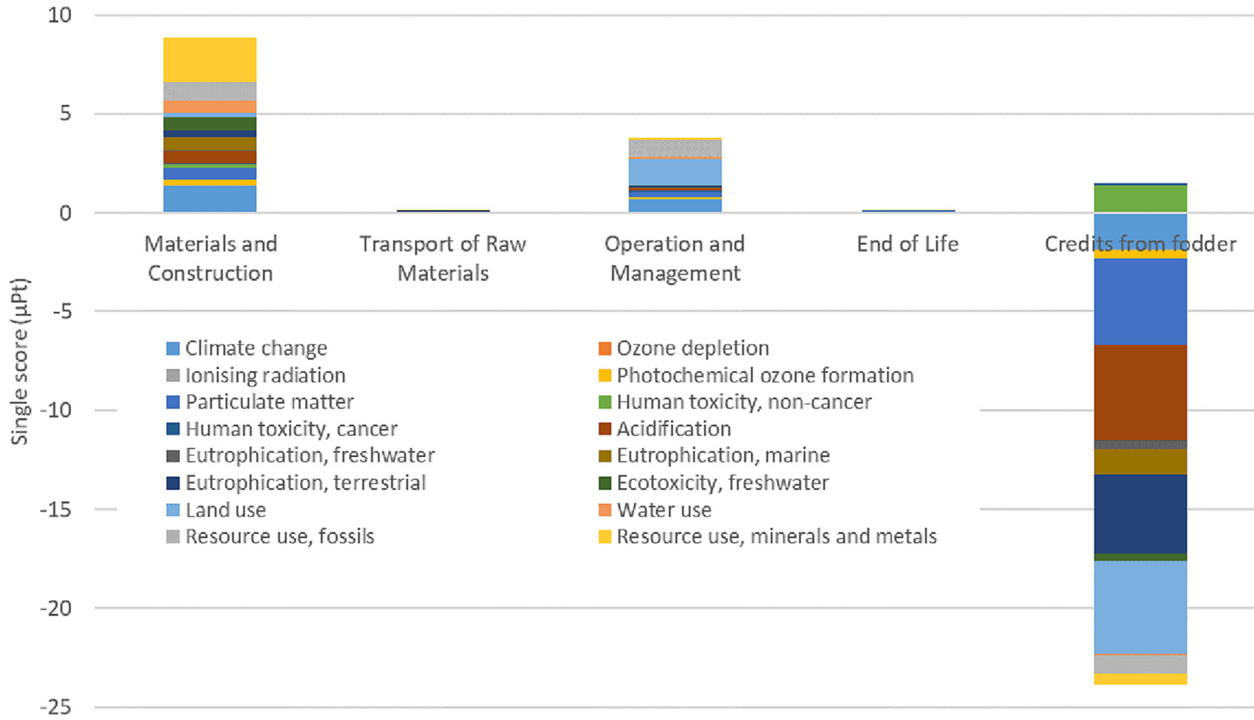


Fig. 5. Single score indicator describing contribution of different life cycle stages and environmental categories of the floating filter.

represent 42.5 % of the GHG emissions calculated for the floating filter (8.21E-02 kg CO_2 eq./m^3). Arguably, the aerobic conditions of the floating filter would limit the anaerobic processes that favour methane production, so the actual GHG emissions generated by the floating filter are likely to be in the lower range of those calculated for other CW. Furthermore, average methane emissions would decline linearly with the TOC of the stream, resulting in 3.49E-03 kg CO_2 eq./m^3 at 1 ppm TOC concentration, which would represent 4.25 % of the climate change emissions calculated for the floating filter.

In relation to N_2O, the average emissions for the three CW technologies amounted to 1.83E-02 kg CO_2 eq./m^3, which represents 22.3 % of the GHG emissions calculated for the floating filter. In any case, it should be noted that these values are subject to high uncertainty and their application to the floating filter analysed in this research is not immediate, due to the differences in the operating conditions of the different technologies.

3.1.3. Analysis of sing score indicator

Fig. 5 provides an overarching environmental view of the floating filter as described by the single score of the EF3.0 impact assessment method (Fazio et al., 2018). This aggregated indicator describes how the environmental credits associated with the production of the fodder for animal feeding (−22.38 μPt) more than compensate the burdens generated by the filter throughout its life cycle (12.92 μPt) to produce net environmental benefits of (9.46 μPt). This compensatory effect had already been outlined in the analysis of characterised impacts (Table 5) which described negative total impact values in 7 of the 16 midpoint categories considered in this methodology. The net environmental benefits of the floating filter described by the single score are primarily associated with the strong credits generated in certain categories such as particulate matter (−4.37 μPt), acidification (4.81 μPt), terrestrial eutrophication (−4.00 μPt) and land use (− 4.71 μPt), which already incorporate the normalisation and weighing factors included in the EF3.0 method. Note that these credits describe (in negative values) the impacts associated with the production of organic grass silage (Grass silage, organic {CH}| production) (Wernet et al., 2016), which is replaced by the biomass silage produced by the floating filter.

The analysis of the single score also confirms the dominance of the M&C stage in the environmental performance of the floating filter, primarily due to impacts on Resource use, mineral and metals category (4.41 μPt) (associated with the fabrication of the PV panels) and climate change (1.80 μPt) (associated with the PV modules and the production of the barley straw). Regarding the O&M stage (totalling 3.79 μPt), the single score is dominated by impacts on the Land use (1.33 μPt), Resource use, fossils (0.81 μPt) and Climate change (0.66 μPt) categories, due primarily to the land occupied by the floating filter, the consumption of plastic film for fodder production and the use of mechanised equipment for biomass harvesting and transport.

3.2. Life cycle cost analysis

The CAPEX of building the floating filter was estimated at 28,458 € (see Table SI 1 in Supplementary Information). This does not include the 6000 € cost of the land since this was supposed to retain its worth (updated for inflation) at the end of the 10-year cycle. Most of this cost (50.8 %) corresponds to the purchasing of the *Typha domingensis* seedlings, followed by the purchase and installation of the energy system (17.4 %), auxiliary materials (plastic mesh, plastic film and straw) (14.3 %) and civil works (15.9 %). It should be noted that while these values describe the capital costs associated with the construction of the floating filter, the LCC analysis takes into consideration the longer lifespans of the civil works (40 years) and energy system (20 years), which retain ¾th and ½th of their worth after the first 10-year cycle.

For a conventional year during the filter's maturity stage (years 1–8), operating costs would add up to 2243 €/year while net revenues from the sale of fodder for animal feeding can be calculated at −1173 €/year, resulting in annual net expenses of 1070 €/year (values not considering inflation and discounts) (see Table SI 2 in Supplementary Information). Most of these costs (57.5 %) are related to personnel for general and technical maintenance activities, 12.5 % to harvesting (including personnel, renting of machinery and plastic for silage) and 26.8 % to water analysis and control. Operating costs are slightly lower in the first year of operation (2103 €), due to the fact that only one harvest is carried out, and slightly higher in the last year (2580 €), due to the additional cost of extracting the submerged biomass. To this latter value, 415 € need to be added to account for the dismantling of the filter at the end of the 10-year cycle. Undiscounted income derived from the sale of silage biomass for animal

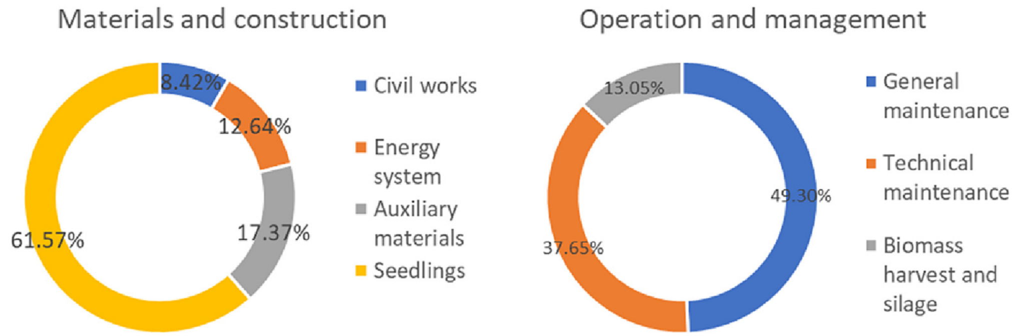


Fig. 6. Contribution of different processes to the life cycle cost of the floating filter.

feeding amounts to 773 € in the first year, 1173 €/year during the maturity stage of the filter (years 1–8) and 2803 € in the last year due to the extraction of both aerial and submerged biomass. Hence, during this period of filter maturity that income from the sale of biomass silage covers 52 % of the operating costs.

The Supplementary Information provides detailed temporal analysis (both discounted and undiscounted) of the life cycle costing (including construction, operation and EoL) and revenues of the floating filter. The results show total discounted (2.5 %) expenses of the floating filter over the 10-year cycle of 44,083 €, with revenues related to the sale of fodder for animal feed amounting to −11,429 €, resulting in a NPV of 32,654 €. These results suggest that although the production of fodder for animal feed leads to very large environmental credits, which even compensate for the impacts generated by the floating filter, the economic revenues associated with this activity are much less significant, representing only 25.9 % of the total discounted expenses.

Taking into account its overall water treatment capacity during the 10-year cycle (108,000 m^3 of water and 1545 kg of N fixed), the total costs of the floating filter (including revenues from fodder sales) may be represented per FU as 0.302 €/m^3 of treated water or 21.1 €/kg of N fixed. These costs compare favourably with those reported by other authors for conventional CWs 0.26–0.89 $€_{2021}$/m^3 (Garfí et al., 2017; Resende et al., 2019b). Cost of large scale urban wastewater treatment in Southern Europe has been reported to range between 0.2 and 0.5 €/m^3, with an average of 0.37 €/m^3 (Pajares et al., 2019). These values are higher in the case of infrastructures intended for lower scale treatment (e.g., activated sludge), whose cost have been estimated at 0.7 €/m^3 of treated water, double of that calculated for the floating filters. In either case it is necessary to emphasise the differences between a conventional wastewater treatment plant (without nitrification/denitrification stage) and a dedicated facility for the removal of diffuse eutrophic pollution, as is the case in this study.

Fig. 3 illustrates that the expenses are distributed evenly between the O&M (53.3 %) and the M&C (45.9 %) stages, while the contribution of the EoL activities are not significant (< 1 % in total). The comparison of LCC and *E*-LCA results leads to the conclusion that activities in the M&C stage are more environmentally intensive than those in the O&M stage, meaning that they generate comparatively more impact per unit of expenditure. This is due primarily to the fact that the economic inventory of the O&M stage includes provisions for staff salaries, which are not accounted for in the environmental analysis. As shown in Fig. 6, most of the costs in the M&C stage stem from the acquisition of the seedlings (61.6 %) while most of the costs incurred during the operation of the floating filter are related to maintenance activities, a budget line that is dominated by the hiring of personnel (93 % of general and 29 % of technical maintenance) and also the cost of analysis for water treatment control (71 % of technical maintenance).

3.3. Uncertainty and sensitivity assessment

The results showed very low relative and absolute variability in the analysis of the floating filter for key impact categories such as climate change, photochemical ozone formation, acidification, terrestrial eutrophication, terrestrial and fossil resource use, with coefficients of variability (CV) in all cases below 4 %. However, uncertainty levels were higher for other impact categories such as human toxicity, cancer (31.6 %) and non-cancer (137 %), freshwater eutrophication (29.8 %) or ozone depletion (27.8 %). The absolute variability (SD) of the results remained within the same value range in all categories when the system boundaries of the LCA model were expanded to include the production of biomass. However, this system expansion caused marked increase in the relative uncertainty of certain categories such as climate change (CV = 81.4 %) which was associated with the lower mean value calculated in this scenario. A complete uncertainty analysis of all the categories included in the EF3.0 method may be viewed in Supplementary Information.

Table 7 describes the sensitivity assessment for carbon footprint and monetary costs associated with a 50 % change in selected input data. The results show that there is no strong correspondence between environmental sensitivity (carbon footprint) and economic sensitivity (monetary costs). For climate change, the most sensitive processes are related to the manufacturing of the energy system (mainly the photovoltaic panels), the production of the cereal straw and the production of the seedling, as well as the plastic used for the silage of the biomass in the operation and maintenance stage. The most cost-sensitive processes are those related to the maintenance of the floating filter and the production of seedlings. Personnel costs, which affect different processes in the construction and operation stage, also show a high sensitivity within the range of variability considered.

As described in Section 2.3.4, direct emissions of CH_4 and N_2O are also an additional source of uncertainty in the carbon footprint analysis of the floating filter. The analysis of a worst-case scenario considering the

Table 7
Sensitivity assessment describing changes in carbon footprint and monetary cost of the floating filter (excluding biomass credits) resulting from modifying specific input data by 50 %.

Hypothesis	Climate change	Cost
	kg CO_2 eq. /m^3	€ / m^3
Materials and construction		
Civil works	1.78 %	2.24 %
Straw	8.18 %	1.24 %
Plastics	4.63 %	2.18 %
Energy system	9.67 %	3.37 %
Seedlings	7.35 %	16.4 %
Operation and management		
Plastic film	8.55 %	
Water analysis		6.1 %
Harvest and silage activities		3.0 %
General maintenance		11.3 %
Technical maintenance		8.7 %
Transport	0.91 %	
Machinery rental costs	–	2.53 %
Overall personnel costs	–	14.5 %

emission factors described for other types of CW shows that these direct emissions could increase the carbon footprint calculated for the floating filter by up to 64.8 %. This analysis does not take into consideration the carbon sequestration capacity described for other types of CW due to the complete lack of information available for floating filters.

Another source of uncertainty relates to other forms of water purification promoted by the presence of the floating filter, beyond nitrogen fixation by macrophytes. The model applied in this investigation does not take into account bacterial denitrification processes (Morrissy et al., 2021) which would increase the filter's capacity to rehabilitate eutrophicated water, thus reducing its environmental impact and costs when represented per unit of nitrogen removed.

4. Conclusions

- The carbon footprint of a floating CW of *Typha domingensis* installed in the Alagón river basin (central Spain) was estimated at 0.082 kg CO_2 eq./m^3. The credits associated with the production of biomass for animal feed (0.070 kg CO_2 eq./m^3) can be subtracted from this value to give a grand total of 0.012 kg CO_2 eq./m^3. Considering the N fixing capacity of the macrophytes, this grand total may be represented as 0.845 kg CO_2 eq./kg N. These values do not include direct emissions of CH_4 and N_2O, the activity of nitrifying bacteria and cleansing capacity of the filter during winter dormancy period, whose contributions are not precisely defined for floating filters.
- Most of the carbon footprint produced by the floating filter (excluding direct emissions) comes from the construction (63.2 %) and the operation (31.1 %) stages. Within the construction stage, significant contributions are made by the auxiliary materials (mainly plastics and cereal straw) needed to build the infrastructure, the energy system (mainly PV panels) and the production of the *Typha* seedlings. This same pattern is replicated in most of the environmental impact categories assessed, including the single score aggregate indicator.
- The discounted expenses of the floating filter over the 10-year cycle amounted to 44,083 € while the revenues derived from the sale of fodder for animal feed amounted to 11,429 €, resulting in a NPV of 32,654 €. These may be represented per FU as 0.302 €/m^3 of treated water or 21.1 €/kg of N fixed. These costs are equally distributed between the construction (48 %) and operation (51 %) stages, while the cost of the construction stage is strongly dominated by the seedlings. These values compare favourable against those reported for surface and sub-surface flow CW and for small scale intensive wastewater treatment technologies. The economic benefits associated with the sale of fodder for animal feeding represent only 26 % of the total discounted expenses.

CRediT authorship contribution statement

Guillermo San Miguel: Conceptualization, Formal analysis, Methodology, Software, Visualization, Writing – original draft. **Isabel Martín-Girela:** Data curation, Formal analysis. **Diego Ruiz:** Conceptualization, Formal analysis, Methodology. **Gregorio Rocha:** Data curation, Formal analysis. **María Dolores Curt:** Conceptualization, Supervision, Project administration. **Pedro Luis Aguado:** Supervision, Funding acquisition. **Jesús Fernández:** Conceptualization, Supervision.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Martin reports financial support was provided by European Regional Development Fund.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.163817.

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