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WATERAGRI

D4.1: Description of Developed Wetland Technologies

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WP4 Nutrient Recovery from Streams

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Author(s)/Organisation(s)	Francesco Chioggia / UNIBO Stevo Lavrnić / UNIBO Marco Grigatti / UNIBO Attilio Toscano / UNIBO Chiara Antonioni / UNIBO Francesco Cavazza / CER Rolf Larsson / ULUND Linus Zhang / ULUND Eriona Canga / ALCN Helmut Schabschneider / ALCN Igor Luketina / ALCN Johannes Kisser / ALCN
Contributor(s)	Mona Arnol (VTT)
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Abstract:	Wetland technologies applied on a farm level can be a useful solution for sustainable water management in the agricultural setting since they can influence water quantity and quality. WATERAGRI has tested different types of wetlands in three European countries - Italy, Austria and Sweden, covering different climate and geographical zones. The tests involved full-scale, pilot scale and prototype systems, which are highly relevant to the project objectives. The results have shown a high capacity of farm wetlands and drainage layers for nutrient and contaminant removal from agricultural runoff. Moreover, these systems can be used for growing crops, and biomass produced that way might be used for energy production or as a soil amendment, increasing the circularity of agricultural production. Finally, wetland system performance can be enhanced through the use of biochar (e.g. for nutrient adsorption) or better aeration conditions (e.g. increase in removal processes), and these aspects were also assessed and discussed.

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2	EDEN MICROFLUIDICS	EDEN	FR
3	FORSCHUNGSZENTRUM JULICH GMBH	FZJ	DE
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Table of Contents

1 Introduction 10
2 Comparison of different wetlands in a farm context 11
2.1 Italian case study description 11
2.2 Results 13
2.2.1 Biochar adsorption trial 13
2.2.2 Effect of the wetland substrate 14
2.2.3 Impact of the wetland type on removal efficiency 14
2.2.4 Nutrient adsorption by wetland plant species 17
2.2.5 Wetland biomass as a compost 18
2.2.6 Full-scale wetland system 23
3 Productive wetland 25
3.1 Swedish case study description 25
3.2 Productive wetlands in a general context 28
3.3 Considerations - Swedish context 29
3.3.1 Edible plants 29
3.3.2 Energy crop 31
3.4 Considerations - Gårdstånga Nygård 33
3.4.1 Edible crops 33
3.4.2 Energy crops 34
3.5 Results - water quality 35
3.5.1 Water Quality in the Farm-Constructed Wetland 35
4 Bioengineering techniques for nature-based systems, biomimicry workshop, and passively aerated prototype (ALCN) 43
4.1 Bioengineering Techniques for nature-based solutions 43
4.2 Biomimicry design workshop for semi-passive aeration of constructed wetlands 48
4.3 An integrated prototype aeration system 50
5 Conclusions 55
6 References 57

WATERAGRI

List of Tables

Table 1 - Material mixtures for compost production. 19

Table 2 - TKN values for the three composts and required amount for the target of 280 kg efficient N ha^{-1}. 19

Table 3 - Aerial parts average TOC (g kg^{-1} dry weight) of the harvested test specimens and standard deviation; and respective ratio to the control (g/g %) 22

Table 4 - Aerial parts average N, P and K content (g kg-1 dry weight) of the harvested test specimens, with standard deviation respective ratio to the control (g/g %) 22

Table 5 - Pollutant load in the inflow and outflow of the FWS wetland 24

Table 6 - Simplified profitability calculation (SEK/yr) for Salix plantation 1 ha, (SBA, 2019). Assumptions described in text. 33

Table 7 - Categories of water sampling and list of elements (analysed either on site or in the laboratory). 35

Table 8 - Linear regression results for TP and TN as displayed in Figure 24 and Figure 25, respectively 41

Table 9 - Seed species planted on Draingarden and soil filter systems (Mistelbach) and the biomass yield after the season 2021(*). 44

Table 10 - Advantages and disadvantages of the passive aeration prototype. 55

List of Figures

Figure 1 - Scheme of the Marsili experimental farm 11

Figure 2 - The full-scale FWS wetland at the Italian case study 12

Figure 3 - The WATERAGRI pilot plant in the Italian case study 12

Figure 4 - Schematic representation of the pilot plant. 13

Figure 5 - SFCW2 effluent concentrations (mg L^{-1}) during the biochar adsorption trial. 14

Figure 6 - Concentrations of nutrients in influent (mg L^{-1}, average ± standard deviation) and effluent of HFCW1 and HFCW2. 15

Figure 7 - Concentrations of nutrients in influent (mg L^{-1}, average ± standard deviation) and effluent of HFCW1 and SFCW1. 16

Figure 8 - Total TP, TN and TOC content in above and below-ground biomass. 17

Figure 9 - Compost bins constructed for the trial. 18

Figure 10 - Randomised lettuce samples in the phytotron during the trial. 20

Figure 11 - Lettuce plants at the end of the experiments; mean dry weight (g) and standard deviation are reported. 21

Figure 12 - Aerial parts average dry weight (g) of the harvested test specimens and standard deviation. 21

Figure 13 - Hydrology of the FWS wetland during the monitoring period 24

Figure 14 - Farm Constructed Wetland, Gårdstånga Nygård. The photo was taken soon after construction during the filling phase 25

Figure 15 - Gårdstånga Nygård wetland system. 1= newly constructed wetland; 2 = older, small wetland; 3 = mature wetland. 26

Figure 16 - The Rödabäck stream. The photo was taken upstream of the inlet to the Gårdstånga Nygård wetland system. 26

Figure 17 - Gårdstånga Nygård. Mature wetland in the forefront and left. Salix plantation next to the wetland in the background and right. 27

Figure 18 - Gårdstånga Nygård. Location of old, small wetland (Lilla Skeglinge 1:1) downstream of new, constructed wetland. Both wetlands are part of the Rödabäck catchment. 27

Figure 19 - Gårdstånga Nygård scheme. Small experimental field with 64 parcels next to the newly Farm Constructed Wetland. North and west of the wetland is the Rödabäck Stream which feeds the wetland. (The markers: USR, Inlet, 1-6, Outlet, P, and DSR are locations 28

Figure 20 - Variations of selected elements during the water sampling period. 37

Figure 21 - Variation of pH and turbidity at different locations during the sampling period. See Figure 18 for sampling points location P = Pump1). 38

Figure 22 - Selected water quality indicators and their variations during the sampling period. 39

Figure 23 - Spatial and temporal trends of COD and BOD5. The horizontal axe represents most upper streams to most downstream. 40

Figure 24 - Linear trend analysis of TP over the wetland for each sampling date in Table 8. 42

Figure 25 - Linear trend analysis of TN over the wetland for each sampling date in Table 8. 42

Figure 26 - Filter design of the bio-inspired filters in Mistelbach, (Austria). 44

Figure 27 - Iterations of structures tested (a, b) until the final design (c), developed by alchemia-nova (ALCN). 46

Figure 28 - Simple sketch for bioengineering techniques addressing agricultural landcover runoff in actual scale applications, alchemia-nova (ALCN). 47

Figure 29 - Sketch for bioengineering techniques addressing subsurface drainage water in real-scale applications, alchemia-nova (ALCN). 48

Figure 30 - The output of the biomimicry workshop in the form of a wetland concept drawing. 50

Figure 31 - The sketch shows the air movement through the piping and the substrate where (1) resembles the intended use case and (2) is for control purposes during the experiment. 51

Figure 32 - Measurements of the prototype setup with the assembly showing the piping with chimney (1), the lamps (2), and the substrate with the box resembling the constructed wetland (3). 52

Figure 33 - Radiation pattern (a), light spectrum (b), drawing of LED lamps simulating the sun in the prototype (c, d). 53

Figure 34 - Air velocity in the substrate with dry conditions and increasing soil thicknesses. 53

Figure 35 - Measurements of air throughput (velocity) extrapolated and decreasing with depth. 54

List of Abbreviations and Acronyms

ACV	Reference compost
Al	Aluminium
As	Arsenic
B	Boron
BOD	Biological oxygen demand
Ca	Calcium
Cd	Cadmium
Co	Cobalt
Cr	Chromium
Cu	Brass
CW	Constructed Wetland
DET	Dewaterability Estimation Test
DO	Dissolved Oxygen
DOC	Dissolved organic carbon
EC	Electrical conductivity
FAO	Food and Agriculture Organization
Fe	Iron
FWS	Free Water Surface
HFCWs	Horizontal-Flows Constructed Wetlands
K	Potassium
Mg	Magnesium
$Mg(OH)_2$	Magnesium hydroxide
Mn	Manganese
Na	Sodium
NH_4-N	Ammonium nitrogen
Ni	Nickel
NO_3-N	Nitrate nitrogen
Pb	Lead
PO_4^{3-}-P	Phosphate phosphorus
SFCW	Surface Flow Constructed Wetland
SMHI	Swedish Meteorological and Hydrological Institute
TF-VFCW	Tidal Flow Vertical-Flow Constructed Wetland
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen

TOC	Total organic carbon
TP	Total Phosphorous
TSS	Total Suspended Solids
WR	Water Retainer
Zn	Zinc

1 Introduction

Among agricultural practices, large use of agrochemicals (nutrients and pesticides) is often recorded, many of which are not fully absorbed by plants. Due to various phenomena, like runoff or leaching, the unabsorbed part of these products is discharged into water systems (Zhu et al., 2020), leading to pollution and problems like eutrophication and toxic algal blooms. A way to decontaminate the polluted water is to use artificial wetlands, man-made systems that simulate the processes occurring in natural wetlands, using different types of plants, substrate and operating conditions (Kadlec & Wallace, 2008).

Several studies in different parts of the world have evaluated wetlands' potential for the removal of nutrients. In Sweden, Kynkäänniemi et al. (2013) have analysed the performance of a CW for the agricultural drainage treatment, showing the capacity of this system in retaining TP and total suspended solids (TSS), 69 kg ha^{-1} yr^{-1} and 30 t ha^{-1} yr^{-1} respectively (Kynkäänniemi et al., 2013). In the Czech Republic, Vymazal et al. (2020) have evaluated the capacity of three horizontal flow CWs (HFCWs) for drainage water treatment, finding that their total nitrogen (TN) removal capacity was, on average 1497 kg ha^{-1} yr^{-1} (Vymazal et al., 2013).

However, better monitoring of these systems is needed to establish their performance in different environmental conditions and types of influents. It also needs to improve their overall operation and management, focusing on increasing removal efficiency.

For example, the aeration conditions in the wetland are a very important factor since the presence of aerobic and anaerobic areas can contribute to removing different compounds. For example, Ilyas and Masih (2018) have studied the influence of three different aeration methods with three flow patterns for phosphorous removal, showing how the tidal flow vertical-flow constructed wetland (TF-VFCW) gives the best results in total phosphorus (TP) reduction.

Among the new media that can be used to improve the performance of wetlands, the use of biochar is emerging. This material is obtained through biomass processing (Deng et al., 2021), and its use can overcome the limitations of traditional media like gravel or sand, which cannot always contribute to a high TN and TP removal. Conversely, biochar favours the creation of a proper environment for nitrifying organisms’ development, promoting nitrogen removal (Deng et al., 2021). Moreover, this material's porous structure enhances the system's reoxygenation, which emphasises and accelerates the reduction of ammonium (NH_4^+) and TN (Deng et al., 2021). Regarding the biochar removal potential of TP, it has been noted that this novel medium, enriched by elements like calcium (Ca), aluminium (Al) and magnesium (Mg), can promote the adsorption of TP compared to traditional substrates. The presence of biochar can also enhance the plant and microorganisms’ growth (Deng et al., 2021), favouring nutrient uptake.

The following chapters overview the WATERAGRI activities connected to the wetland systems in three case studies - Italy, Sweden and Austria.

2 Comparison of different wetlands in a farm context

The following chapters give an overview of the WATERAGRI activities in the Italian case study that investigated the effect of different wetland types on agricultural drainage water treatment, as well as the capacity of these systems for nutrient recovery recycling.

2.1 Italian case study description

The Italian case study was located at the experimental farm Marsili managed by CER, while the project activities were jointly conducted by UNIBO and CER.

The farm has an area of 12.5 ha and is used for agricultural production and experimentation with different crops (Figure 1). Due to the application of a precise irrigation approach, no excess water is given to the crops, and therefore the drainage water production occurs only during rain events. An integral part of the farm is a full-scale free water surface (FWS) wetland system that treats agricultural drainage water from the farm area, and that is collected in a single drainage ditch.

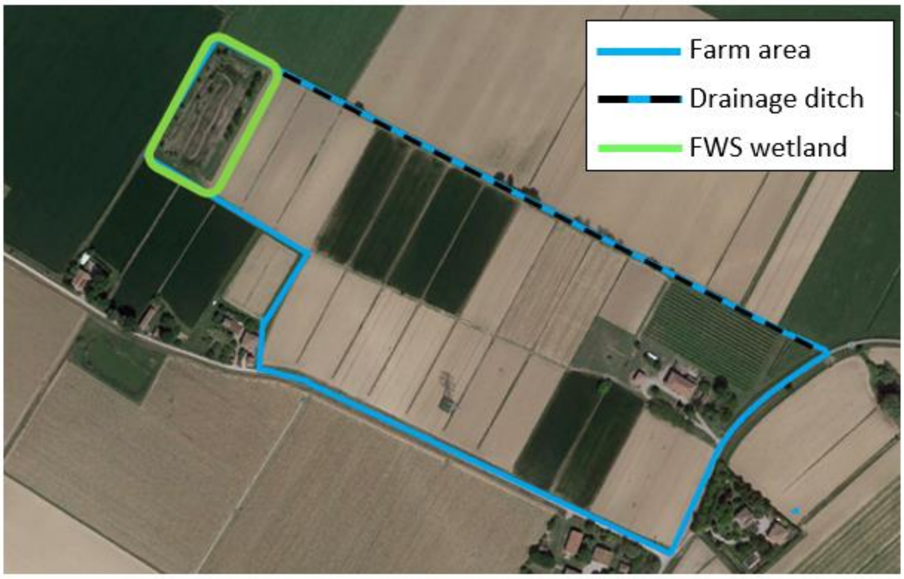

Figure 1 - Scheme of the Marsili experimental farm

The main focus of the Italian case study in WATERAGRI is nutrients recovery from agricultural drainage water and the evaluation of possible nutrient recycling for agricultural production to reduce the use of artificial fertilisers. Such activities comprise the full-scale system and a pilot plant based on constructed wetlands technology, which was built specifically for the WATERAGRI project.

The full-scale surface flow constructed wetland (SFCW) (Figure 2) has a surface area of around 0.4 ha and a 480 m long water course divided into different meanders (Lavrnić et al., 2018; Lavrnić et al., 2020a). It was constructed in 2000 and has been operational since. However, if the precipitation is absent for long periods, the system is mostly in dry conditions. The FWS wetland is fully equipped for inlet and outlet volumetric measurement and sampling and for water level measurement.

Figure 2 - The full-scale FWS wetland at the Italian case study

To investigate the effect of different CW types on the drainage water nutrient treatment, a pilot plant (Figure 3) was built in April 2022 consisting of 4 different systems:

- HFCW1: 200 x 100 x 90 x 80 cm (length x width x substrate height x water level), that uses gravel as a substrate and is planted with *Phragmites australis*;
- HFCW2: 200 x 100 x 90 x 80 cm (length x width x substrate height x water level), that uses gravel (90% of the total substrate volume) and biochar (10% of the total substrate volume) as substrates and is planted with *Phragmites australis*;
- SFCW1: 200 x 100 x 30 x 90 cm (length x width x substrate height x water level) that uses gravel as a substrate and is planted with *Phragmites australis*;
- SFCW2: 200 x 50 x 30 x 30 cm (length x width x substrate height x water level) that uses biochar as a substrate and is not planted.

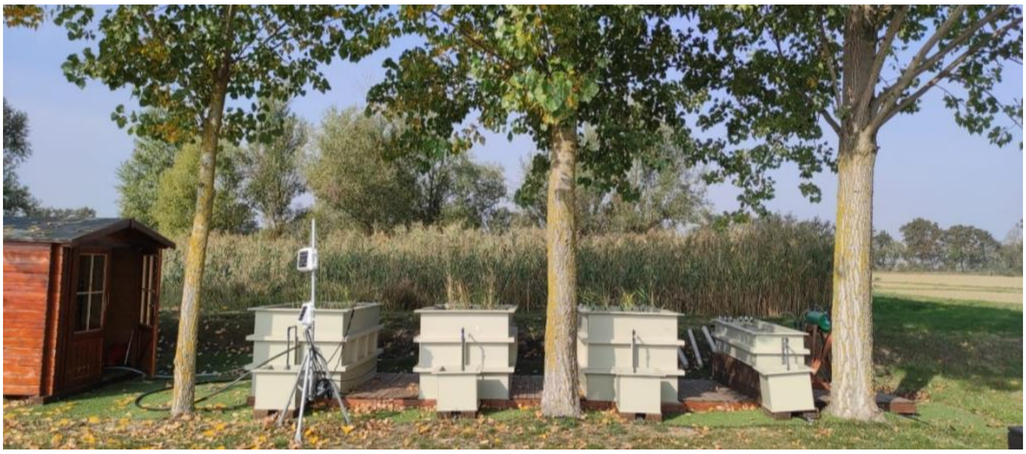

Figure 3 - The WATERAGRI pilot plant in the Italian case study

The scheme of the pilot plant and its different components is given in Figure 4. Due to the scarce precipitations during the experimental period, the drainage water availability was rather low. Therefore, synthetic wastewater with a similar concentration of nutrients was used (Lavrnić et al., 2020b), being prepared with nitric and phosphoric acid.

The employed biochar was purchased from the company CharLine (Riedlingsdorf, Austria) as decided by WP4 partners. It was made of pyrolysed untreated wood chips, characterised by a dry surface area of 292 $m^2 g^{-1}$ and a bulk density of 218 kg m^{-3}.

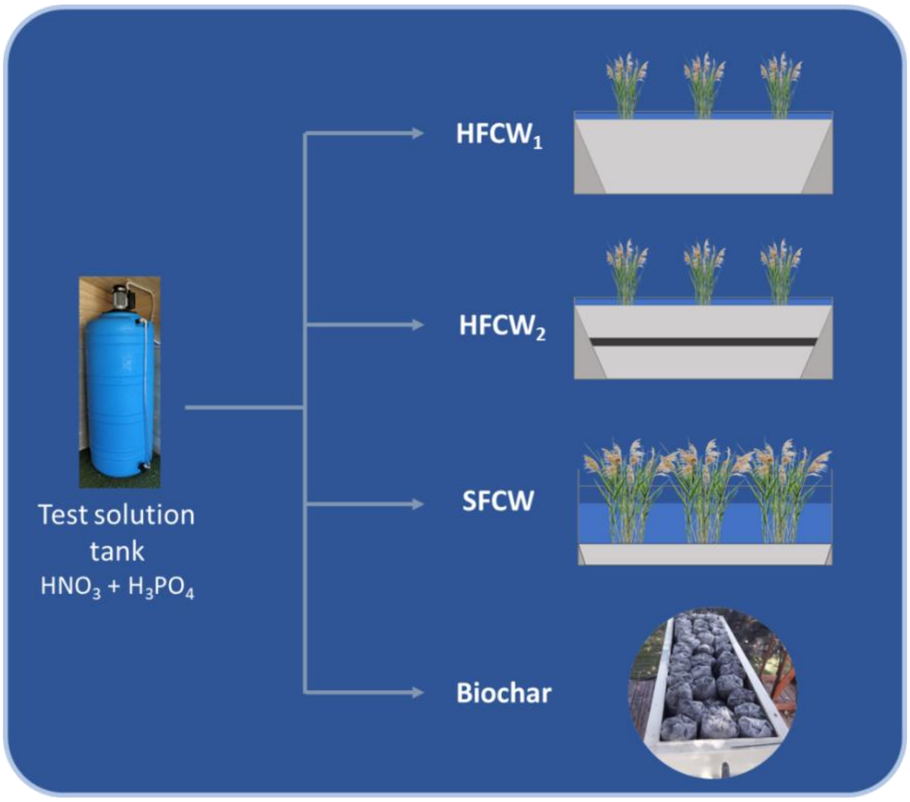

Figure 4 - Schematic representation of the pilot plant.

2.2 Results

2.2.1 Biochar adsorption trial

To establish the maximum amount of nitrogen and phosphorus that the used biochar can adsorb, the experiment using the SFCW2 was performed between 27 July and 16 September 2022 by UNIBO and CER. The influent concentrations were in the range of 40-65 mg L^{-1} for NO_3^--N and 19-31 mg L^{-1} of PO_4^{3-}-P, while the effluent concentrations are given in Figure 5.

It can be observed that the output concentrations experienced a reduction in the first experimental phase (26 July - 8 August), suggesting the potential of the employed material. After the initial phase, the output concentrations tended to increase progressively; this aspect may be compatible with a dynamic of saturation of the biochar active sites and competition between the studied chemicals, which would reduce and eventually nullify its adsorption capacity.

The studied biochar could adsorb 4.37 g N kg^{-1} and 0.43 g PO_4^{3-}-P kg^{-1} and, therefore, presented the capability for nutrients uptake; further studies may be carried out to better assess its saturation kinetics and to experiment with the application as a soil amendment and for nutrients release.

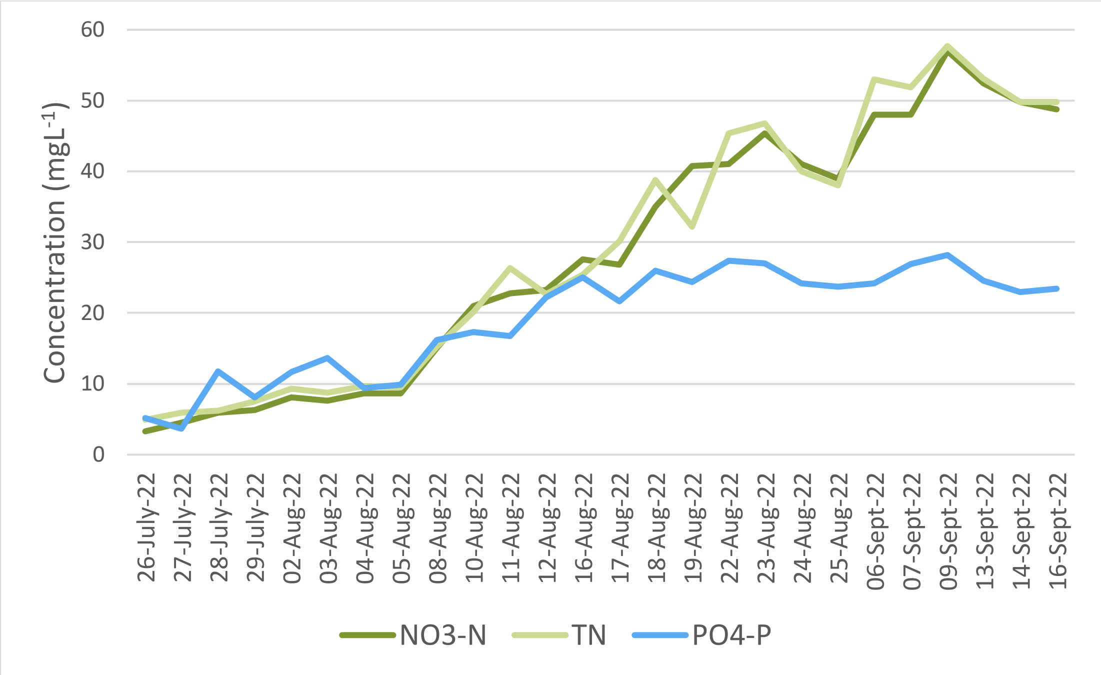

Figure 5 - SFCW2 effluent concentrations (mg L^{-1}) during the biochar adsorption trial.

2.2.2 Effect of the wetland substrate

Since it was shown that biochar could contribute to nutrient removal in CWs, the trial was run using the HFCW1 and HFCW2 to evaluate their treatment performance. The influent values were 19.2±8.4 mg L^{-1} for NO_3^--N, 20.3±7.8 mg L^{-1} for TN and 2.5±0.8 mg L^{-1} for PO_4^{3-}-P in HFCW1 and 17.7±7.2 mg L^{-1} for NO_3^--N, 17.9±6.3 mg L^{-1} for TN and 2.6±1.0 mg L^{-1} for PO_4^{3-}-P in HFCW2. The effluent data of the two systems are represented in Figure 6.

There was no significative statistical difference in terms of NO_3^--N and TN processing: the output concentrations resulted in to fall in the input range. Regarding PO_4^{3-}-P, HFCW2 was characterised by slightly lower output concentrations at the beginning of the trial; such parameter rose after December, while HFCW1 presented lower and falling values.

2.2.3 Impact of the wetland type on removal efficiency

Similarly, HFCW1 and SFCW1, containing gravel as a substrate and planted with Phragmites australis, were used to evaluate the CW type effect on nutrient removal. The influent values were 19.2±8.4 mg L^{-1} for NO_3^--N, 20.3±7.8 mg L^{-1} for TN and 2.5±0.8 mg L^{-1} for PO_4^{3-}-P in HFCW1 and 19.7±8.4 mg L^{-1} for NO_3^--N, 20.3±7.7 mg L^{-1} for TN and 2.5±0.8 mg L^{-1} for PO_4^{3-}-P in SFCW1. The experimental data are given in Figure 7.

Figure 6 - Concentrations of nutrients in influent (mg L^{-1}, average ± standard deviation) and effluent of HFCW1 and HFCW2.

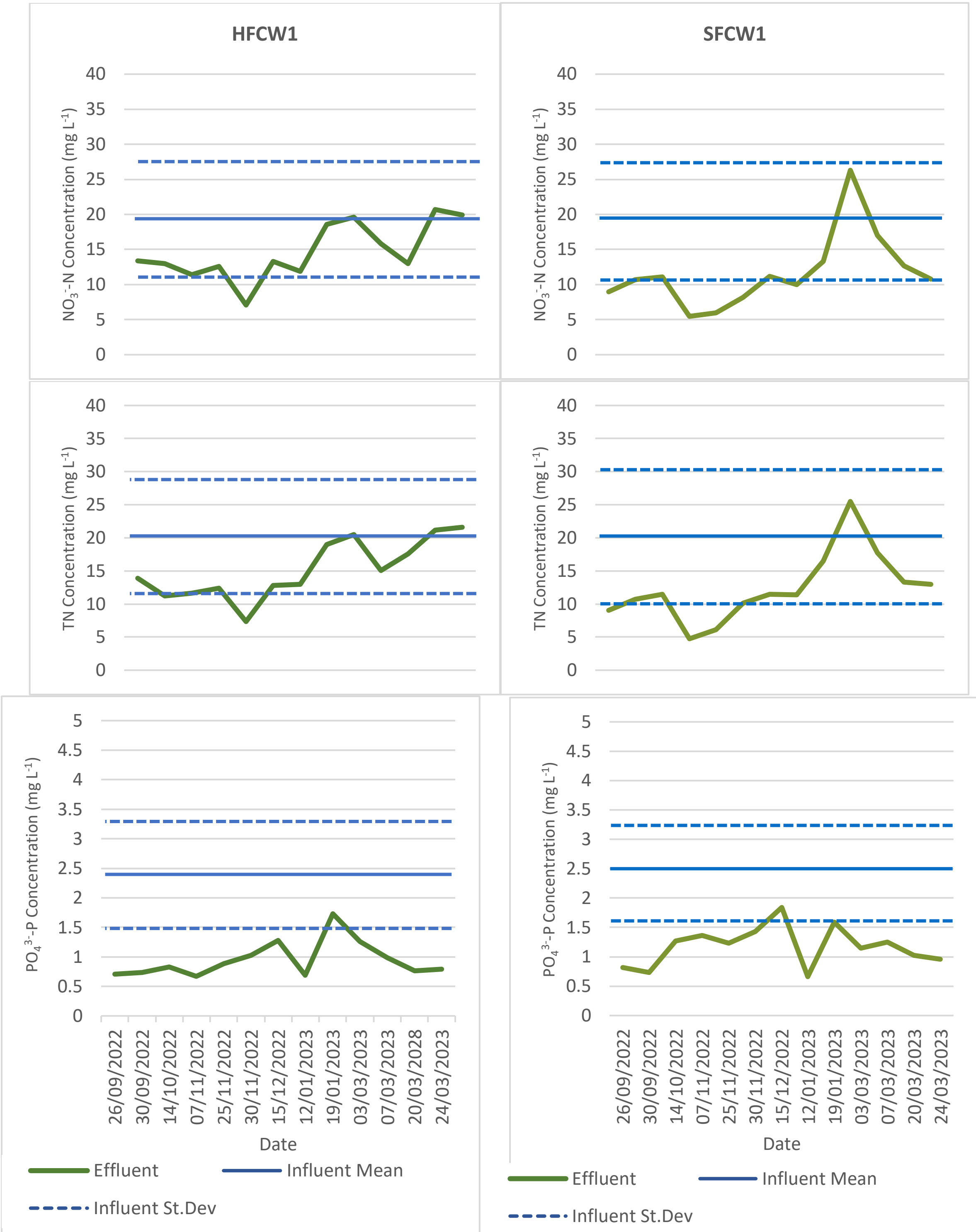

Figure 7 - Concentrations of nutrients in influent (mg L^{-1}, average ± standard deviation) and effluent of HFCW1 and SFCW1.

The SFCW1 presented better NO_3^--N removal than the HFCW1: while HFCW1 presented concentrations of the N forms that were generally included in the influent variability range, more SFCW2 output values were lower than the input. The higher oxygen exchange rate granted by the second setup may have improved the metabolism within the system, allowing the alternation of aerobic and anaerobic processes, which is fundamental for N removal (Vymazal, 2010). No significant statistical difference was observed for TN. Regarding PO_4^{3-}-P, HFCW1 was characterised by slightly lower output concentrations than SFCW1. This aspect may be related to the higher content of substrate in the horizontal flow system, which could have presented a higher surface capable of phosphorus adsorption and filtration, thus promoting its removal from wastewater (Vohla *et al.*, 2011).

2.2.4 Nutrient adsorption by wetland plant species

The choice of the species planted inside the system is very important, as some are more suitable to treat water than others, and they have a different capacity to uptake and store nutrients. Within the full-scale SFCW, *Phragmites australis*, *Carex spp*. and *Typha latifolia* are the main species present, even if the first one covers the biggest surface. Figure 8 displays the content of each species in the FWS wetland between 2019 and 2021.

Figure 8 - Total TP, TN and TOC content in above and below-ground biomass.

Slight differences can be found among the three species investigated for different years, but, on average, TP, TN and TOC content was higher in the above-ground biomass than in the below-ground one, and *Carex spp.* had higher content compared to the other two species. Looking at the single elements, it can be said that *Typha latifolia* tended to store more TP in the above-ground biomass than the other two species, while *Carex spp.* tended to accumulate more TN and TOC.

2.2.5 Wetland biomass as a compost

Since the wetland plants can absorb nutrients, harvested above-ground biomass could be used for composting to close the loop and enable the reduction in chemical fertilisers use. However, the nutrient content of the above-ground biomass, addressed above, is not the only parameter to consider when deciding what plant species are suitable for composting. Another important factor is the ratio between TOC and TN: correct proportions are fundamental for the metabolism of the microorganisms responsible for the composting process and for fast development. A C/N ratio of 30:1, up to a maximum of 50:1, is suggested by the Italian Legislative Decree 75 of 29 April 2010 for the production of green composts, which would promote the degradation of the organic carbon (Decreto Legislativo 29 aprile 2010).

At higher N levels, a such element would be in excess and potentially lost as ammonia. Considering the data of the aerial parts (Figure 8), the plants showed the following average C/N ratios: 33.8 for *Carex spp*, 44.0 for *Phragmites australis*, and 55.5 for *Typha latifolia*. The latter (*T. latifolia)* was outside the recommended range, considering the low biomass production of *Carex spp*. (12-25 g m^{-2} *vs* 3100 g m^{-2} of *Phragmites australis*) and the distribution in the CW, *Phragmites australis* was selected as biomass for compost production (Solander, 1983; Rezania *et al.*, 2019).

2.2.5.1 Compost production

The studied compost was produced within the full-scale SFCW: fresh *Phragmites australis* (reed) plants were cut, chipped down to 2 cm in size and placed in *ad-hoc* constructed compost bins of 1 m^3 (Figure 9).

Figure 9 - Compost bins constructed for the trial.

To evaluate the potential of the compost alone and in combination with other recovery products, three different composts were consequently produced (Table 1): i) reed alone (compost “P”), ii) reed and potato plant above-ground biomass from the Marsili farm (compost “PP”), and reed added with liquid digestate (5.8 g TN pet kg of wet matter) (compost “PD”). The three biomass mixes were left composting for 2.5 months, during which they were maintained wet and periodically mixed. After the composting period, an aliquot from each bin was extracted, air-dried at room temperature, ground to 2 mm and kept in sealed plastic bags.

Table 1 - Material mixtures for compost production.

Name	Substance	Weight (kg)	Dry weight (%)
PD	Reed	22.52	59.51
	Digestate	13.32	6.10
PP	Reed	15.33	59.51
	Potato Cuttings	46.32	21.41
R	Reed	27.15	59.51

2.2.5.2 Preliminary analyses and pots preparation

For evaluating the required amount of compost to be applied for the crop growth, an aliquot of each dried compost and a reference compost (ACV) were milled and analysed for the Kjeldahl N content (Table 2). Since the ACV value derives from a certified analysis, no standard deviation is reported.

Table 2 - TKN values for the three composts and required amount for the target of 280 kg efficient N ha^{-1}.

	Compost TKN (mg g^{-1})	Required compost (g kg^{-1})
PD	14.63 ± 0.05	18.41
PP	17.27 ± 0.06	15.59
R	14.30 ± 0.48	18.83
ACV	19.80	13.60

In total, 30 pots were prepared with a base of non-woven fabric and approximately 150 mL of 1 mm dried sand to provide a layer for the drainage of excess water. The different composts were applied based on the TKN preliminary results and the recommended application in agriculture of 280 kg efficient N per ha of cultivated soil (Table 2). After the compost addition, the mixes were carefully homogenised and 3 pots were prepared with each mix to create a triplicate for the trials that follow:

- PP Compost;
- PD Compost;
- R Compost;
- ACV Compost;
- Unfertilised control (“Ctrl”);
- Chemical NPK fertilisation (“Chem”).

The plant chosen for the trial, *Latuca sativa*, var. Romana (lettuce) was cultivated in the experimental setup described above.

2.2.5.3 Trial

The pots prepared were randomly placed in a phytotron (Figure 10), with controlled humidity (45%), temperature (22 - 26 °C) and light exposure (approximately 15000 lux), and equally irrigated with tap water every 3 days. Rotation of the pots occurred every 15-20 days to grant homogeneous conditions for all the plants. After 18 and 35 days, the chemical fertiliser solutions were applied to the chemical control pots, adding 182 mg of N and 45 mg of P.

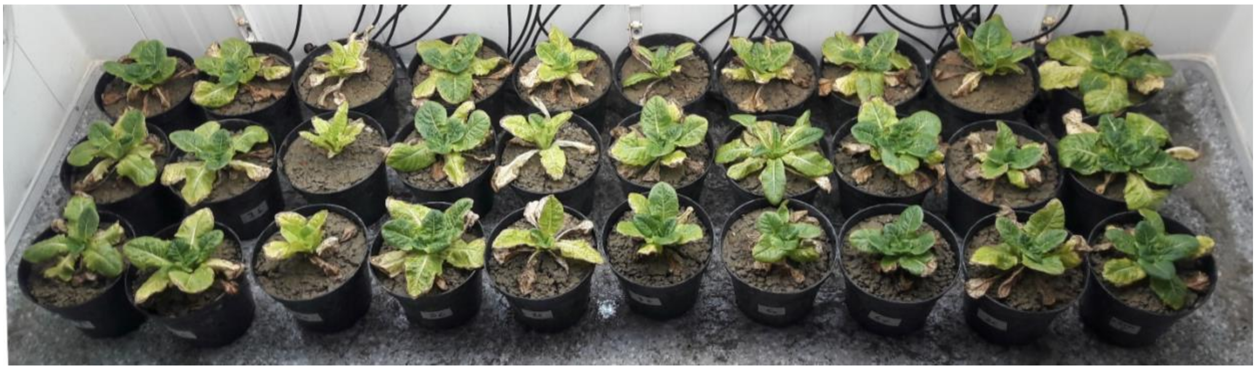

Figure 10 - Randomised lettuce samples in the phytotron during the trial.

The plants were harvested at the end of the 2nd month of the experiment, separating the aerial part and the soil for differentiated analyses; pictures were taken to have a visual analysis as well. The plant parts were dried in a ventilated oven at 60 °C for 2 days. The soil was placed in an aerated room and dried at room temperature (c.a. 22 °C) for several days. Once dried, the samples and the compost were milled and analysed for TN and elemental composition.

2.2.5.4 Results

Figure 11 depicts the status of the plants at the end of the experiments. The average dry weight of the harvested aerial part and the standard deviation, is reported in Figure 12. Apart from the chemical control, which generated 3.1 ± 0.9 g of dry leaves (+48% compared to ctrl, wt/wt. %), PP compost-treated plants resulted as the most productive specimens, yielding an average dry weight of 2.8 ± 0.3 g (130% compared to ctrl, wt/wt. %). The thesis outclassed the AVC reference, which produced 2.3 ± 0.1 g (108% compared to ctrl, wt/wt. %) of dry mass. PD resulted in being less performing, yielding plants with an average dry weight of 1.7 ± 0.5 g (78% compared to ctrl, wt/wt. %), worse than the unfertilised control, which produced 2.1 ± 0.4 g of dry matter. The worse performing thesis was R, whose lettuce plants yielded only 0.9 ± 0.4 g (45% compared to ctrl, wt/wt. %) of the dry aerial part.

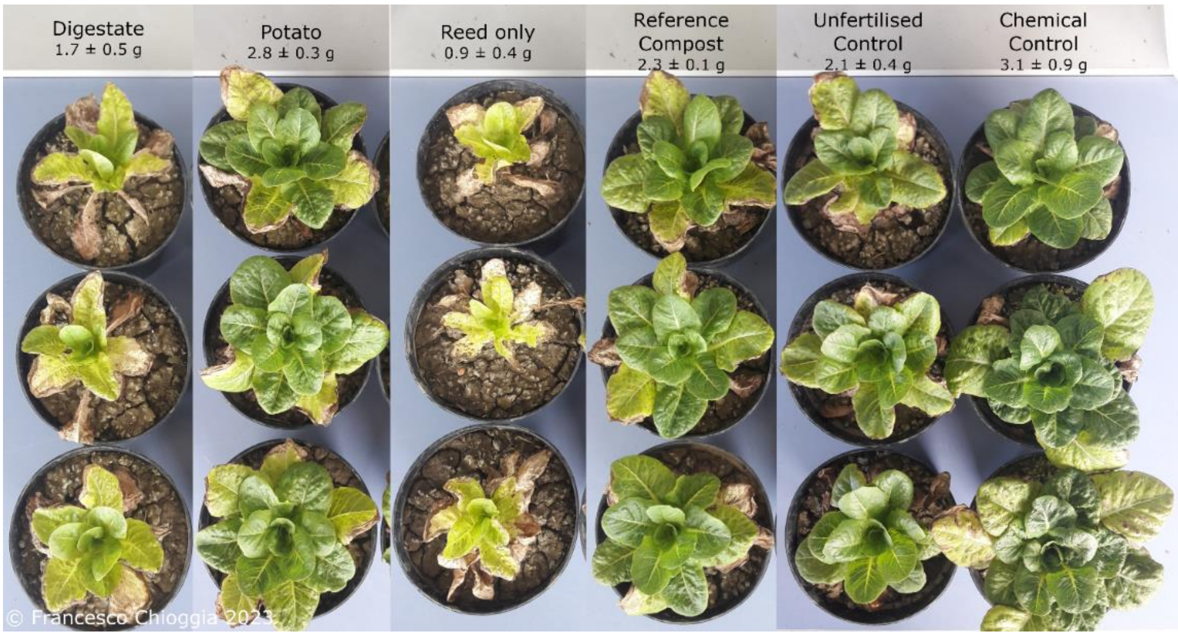

Figure 11 - Lettuce plants at the end of the experiments; mean dry weight (g) and standard deviation are reported.

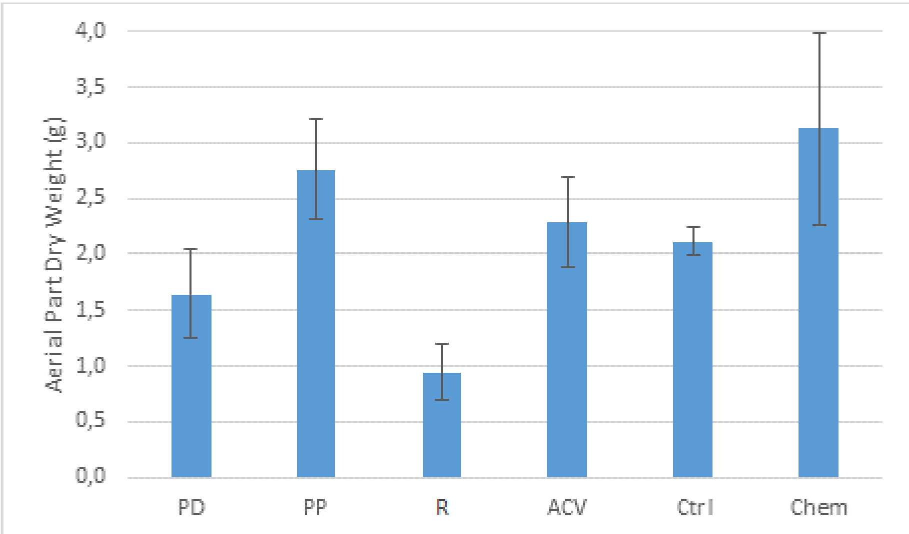

Figure 12 - Aerial parts average dry weight (g) of the harvested test specimens and standard deviation.

Table 3 reports the data obtained from the TOC analysis of the harvested lettuce aerial parts. No statistically significant difference was observed among the samples. The P and K content on dry weight were measured on the composts. The PP reed-potato mix presented the highest concentrations (2.2

P and 10.8 g K kg^{-1}) compared to the other two WATERAGRI composts, which presented similar concentrations: PD (1.5 g P and 4.9 g K kg^{-1}) and R (1.2 g P and 5.0 g K kg^{-1}).

Table 3 - Aerial parts average TOC (g kg^{-1} dry weight) of the harvested test specimens and standard deviation; and respective ratio to the control (g/g %)

	TOC	
	(g kg^{-1})	Treatment/Ctrl (%)
PD	563 ± 70	108
PP	575 ± 55	111
R	508 ± 51	98
ACV	594 ± 32	115
Ctrl	519 ± 34	-
Chem	569 ± 80	110

Table 4 reports the data obtained from the P and K analyses of the harvested lettuce aerial parts. Compatible with the previous observations, the chemical reference had processed more nitrogen than the other theses, presenting a TN content of 38.5 ± 7.4 g kg^{-1} (150% elemental content (sample)/elemental content (ctrl), %) of dry matter. The second most N-absorbing plants resulted in being the ACV-treated ones, characterised by an N content of 27.9 ± 2.1 g kg^{-1} (109% elemental content (sample)/elemental content (ctrl), %). The trend observed for the three constructed wetland-related produced composts was confirmed with the analyses: PP resulted the best, with a TN content of 23.1 ± 2.0 g kg-1 of dry matter (90% elemental content (sample)/elemental content (ctrl), %), followed by PD with 13.8 ± 1.6 g TN kg^{-1} (54% elemental content (sample)/elemental content (ctrl), %) and by R, with 9.8 ± 0.6 g TN kg^{-1} (38% elemental content (sample)/elemental content (ctrl), %).

Table 4 - Aerial parts average N, P and K content (g kg-1 dry weight) of the harvested test specimens, with standard deviation respective ratio to the control (g/g %)

	N		P		K	
	g kg^{-1}	Treatment/Ctrl (%)	g kg^{-1}	Treatment/Ctrl (%)	g kg^{-1}	Treatment/Ctrl (%)
PD	13.8 ± 1.6	54	1.1 ± 0.2	119	26.2 ± 5.2	69
PP	23.1 ± 2.0	90	0.9 ± 0.2	97	301 ± 13	81
R	9.8 ± 0.6	38	1.5 ± 0.3	161	39.9 ± 2.4	106
ACV	27.9 ± 2.1	109	0.9 ± 0.1	101	38.3 ± 2.7	101
Ctrl	25.6 ± 2.4	-	0.9 ± 0.2	-	37.8 ± 4.0	100
Chem	38.5 ± 7.4	150	1.1 ± 0.1	119	26.6 ± 5.0	70

Regarding P and K uptake, compost R-treated plants showed a slightly higher character, with 1.5 ± 0.3 g P kg^{-1} (161% elemental content (sample)/elemental content (ctrl), %) and 39.9 ± 2.4 g K kg^{-1} (106% elemental content (sample)/elemental content (ctrl), %), higher than the chemical reference. The rest of the theses did not present statistical differences.

The observed behaviour may be related to a response towards the C/N compost ratio-related stress that could have impaired normal plant metabolism and reduced nitrogen mobility.

Reed-potato mix-treated specimens presented the best health and highest macronutrients content amongst the WATERAGRI composts, considering its composition, *i.e.* higher P and K content, as well as a higher TKN concentration of the dry mass (17.27 g N, 2.2 g P and 10.8 g K kg^{-1}), this compost may have been a more balanced addition to the soil, which granted better plant metabolism. Reed-digestate mix compost presented a macronutrients content similar to the reed-only compost - PD (14.6 g N, 1.5 g P and 4.9 g K kg^{-1}) and R (14.3 g N, 1.2 g P and 5.0 g K kg^{-1}); this may have caused the situation unfavourable for plant growth.

2.2.6 Full-scale wetland system

The water flow through the full-scale FWS wetland was monitored in terms of volumetric and quality aspects between April 2020 and September 2022 for 30 months. As previously said, its operation depends highly on the presence of precipitation, and in its absence, the system is dry. Moreover, the output from the system is present only when the water level is above 40 cm.

To facilitate the results visualisation and discussion, the monitoring period was divided into seasons:

- Spring - April, May, and June
- Summer - July, August, and September
- Autumn - October, November, and December
- Winter - January, February, and March

The hydrology of the FWS wetland is given in Figure 13. It can be seen that while the inflow was present in all the monitoring periods, the outflow was concentrated in only two seasons - Summer and Autumn 2021, more specifically in September and October. The system had the highest inflow in that period, as can also be seen from the average water level, which explains the presence of outflow. It should be said that the monitoring period was quite a dry one since the total precipitation during these 2,5 years was around 1200 mm, while the 30-year normal precipitation value in that area is around 770 mm $year^{-1}$ (Lavrnić et al., 2018).

Moreover, there does not seem to be any pattern in seasonal precipitation and inflow to the FWS wetland. For example, in the Springs of 2020 and 2021, the system had almost no inlet, while Spring of 2022 was definitely wetter. Moreover, the summers of 2020 and 2021 were much dryer than the Summer of 2021, which had the highest water inflow of all seasons.

The removal efficiency of the system was assessed in the same period (April 2020 - September 2022). The parameters considered were Chemical oxygen demand (COD), Total organic carbon (TOC), Total suspended solids (TSS), Total nitrogen (TN) and nitrate-nitrogen (NO_3-N). Phosphorus, another important nutrient present in agricultural drainage water, was shown to be low in this case study (Lavrnić et al., 2020), and therefore it was not considered further.

The results of the water quality monitoring are given in Table 5. The pollutant with the highest load was TSS, which is probably a consequence of the soil loss from the agricultural area. The highest inflow loads of this parameter and TOC were recorded in Summer of 2021, while for TN and NO_3-N, it was in the Autumn of 2020.

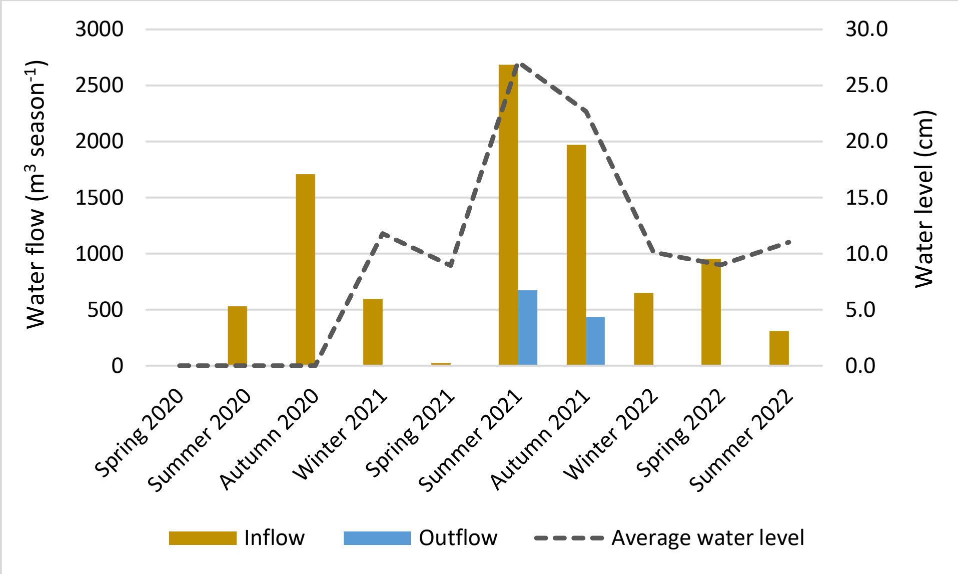

Figure 13 - Hydrology of the FWS wetland during the monitoring period

Table 5 - Pollutant load in the inflow and outflow of the FWS wetland

	TOC		TSS		TN		NO_3-N	
	Inflow (kg)	Outflow (kg)	Inflow (kg)	Outflow (kg)	Inflow (kg)	Outflow (kg)	Inflow (kg)	Outflow (kg)
Spring 2020	-	-	-	-	-	-	-	-
Summer 2020	14.3	-	54.3	-	3.0	-	0.8	-
Autumn 2020	37.0	-	173.0	-	59.2	-	46.3	-
Winter 2021	13.5	-	66.4	-	10.9	-	6.6	-
Spring 2021	-	-	-	-	-	-	-	-
Summer 2021	58.3	26.8	519.0	41.0	4.0	0.9	3.5	0.4
Autumn 2021	56.9	15.8	123.0	50.9	1.7	0.5	0.6	0.2
Winter 2022	19.0	-	51.6	-	0.6	-	0.3	-
Spring 2022	14.1	-	246.1	-	3.2	-	4.2	-
Summer 2022	7.5	-	88.8	-	0.3	-	0.5	-

As for the efficiency of the pollutants treatment, it can be seen that the system achieved rather high removal rates in the Summer and Autumn of 2021 when effluent from the system was present. This is especially true for the Summer season, which could be connected to the higher temperatures in that period and, therefore, higher biological activity.

All the removal rates were above 50%, showing the FWS wetland's capacity to treat agricultural drainage water even 20 years after its construction and confirming the potential of this technology in the agricultural setting. Moreover, in the absence of effluent in other seasons, it can be hypothesised that the pollution load that entered the system was also degraded, further supporting the efficiency of the FWS wetland.

3 Productive wetland

3.1 Swedish case study description

Gårdstånga Nygård (GN) is a farm located 9 km north of Lund, Sweden, at lat 55.7, long 13.3. The farm has a continental climate with an average precipitation of 750 mm per year, an average annual temperature of 7.5°C and annual evapotranspiration of typically 420 mm (SMHI, 2011). The soil type is sandy, stony loam with an average of 20% clay.

The farm area is 1000 hectares which are farmed conventionally according to the FAO principles of Conservation Agriculture FAO (2022) in a non-ploughed system with minimal soil disturbance. The non-ploughed farming system has reduced the consumption of fuel by 50% as well as further stabilised the nutrients in the soil with reduced leakage.

Sustainable nutrient and water retention management at GN includes a new (2020) Farm Constructed Wetland, which has the multiple purposes of reducing nutrient release to the natural waters, increasing biodiversity and providing water for irrigation (Figure 14). The new wetland, with a surface area of 3 ha, is part of a system of different wetlands (map, Figure 15) including two wetlands downstream of the new one, all situated within a distance of three kilometres. The wetlands are fed by a small stream, Rödabäck, with a catchment area at the inlet to the new wetland of 6.5 km^2.

Figure 14 - Farm Constructed Wetland, Gårdstånga Nygård. The photo was taken soon after construction during the filling phase

The stream, Rödabäck, which receives most of its flow from surrounding agricultural fields, is quite small, with vegetation covering both the channel bottom and sides (Figure 16). Therefore, it functions as a vegetated wetland channel in the system. It adheres to descriptions/definitions in both the US and New Zealand: "*Constructed wetland channels use dense vegetation to slow down runoff and allow time for both biological uptake and settling of sediment*" (MHFD, 2010); "*Elongated wetland channel receiving sub-surface tile drainage. …This is followed by a shallow fully vegetated zone (≥70 % of the area) promoting microbial denitrification and plant uptake.*" The original strategy for the wetland system included using part of the system for growing edible crops. This possibility has been carefully evaluated, and the assessment is presented in this report. An alternative strategy for implementing a productive wetland is to grow energy crops, more specifically willow (*Salix*), that are presently grown next to the mature wetland (Figure 17). A new plantation of *Salix* for energy is planned for the older small wetland, see Figure 18. This strategy has been analysed and further developed for GN.

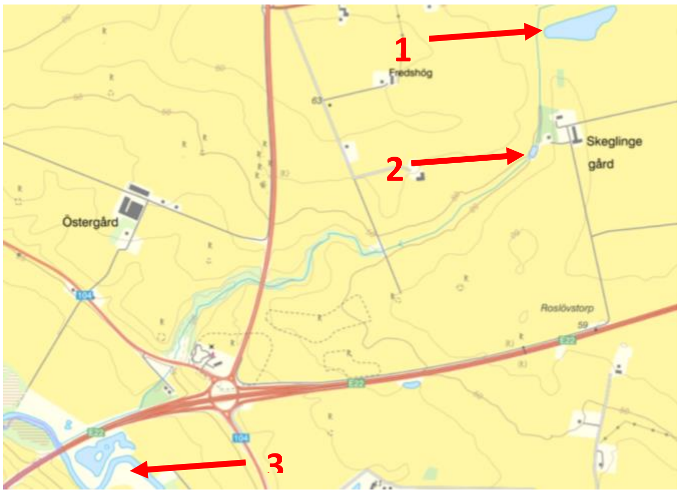

Figure 15 - Gårdstånga Nygård wetland system. 1= newly constructed wetland; 2 = older, small wetland; 3 = mature wetland.

Figure 16 - The Rödabäck stream. The photo was taken upstream of the inlet to the Gårdstånga Nygård wetland system.

Figure 17 - Gårdstånga Nygård. Mature wetland in the forefront and left. Salix plantation next to the wetland in the background and right.

Experiments and field studies

While this report focuses on nutrient retention, various experiments and field studies have also been carried out at GN to support the development and evaluation of other WATERAGRI solutions. A small experimental field (Figure 19) with 64 parcels has been planted with winter wheat (growing season 2020/2021) and with spring barley (growing season 2022). Some of the parcels were sprayed with Water Retainer (WR) (solution B5). The effects of WR on soil microbiology were investigated and reported in D3.2 (Assessment of Water Retention Methods). Effects of WR on crop production have been investigated and reported in D5.3 (Data collected from case studies). The Dewaterability Test apparatus (DET, solution B8) has been tested with sediment samples from one of the GN wetlands, the results of which are described in D5.3.

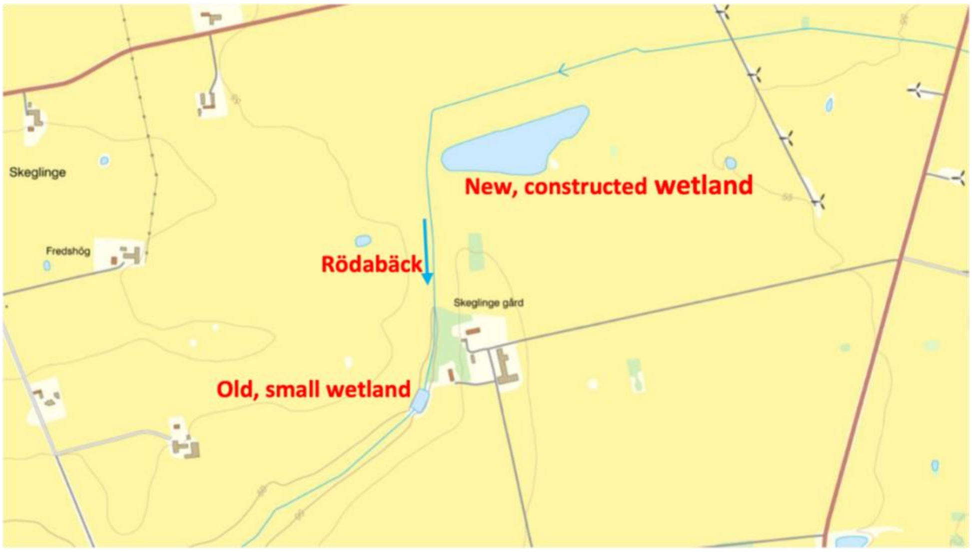

Figure 18 - Gårdstånga Nygård. Location of old, small wetland (Lilla Skeglinge 1:1) downstream of new, constructed wetland. Both wetlands are part of the Rödabäck catchment.

Water quality in the new GN wetland has been studied by regular sampling at various points in and around the wetland. Results are presented in D5.3 and are further described in section 3.4.

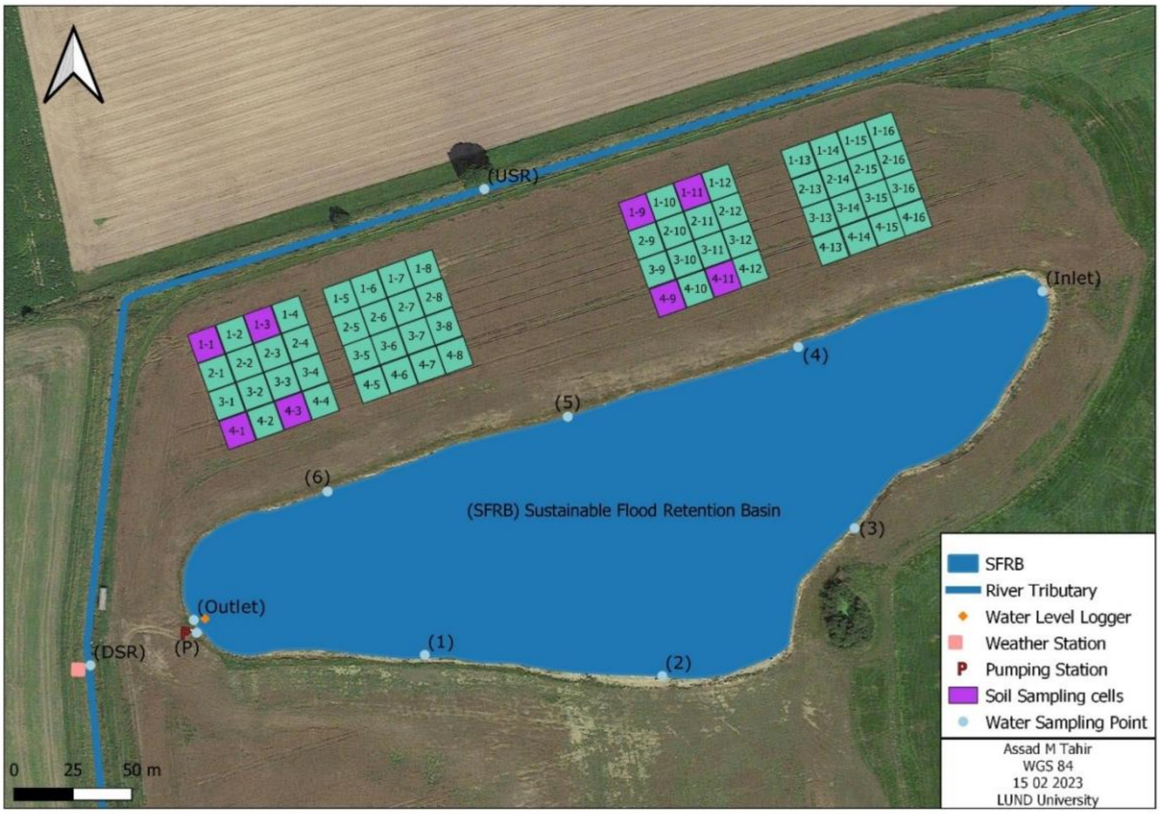

Figure 19 - Gårdstånga Nygård scheme. Small experimental field with 64 parcels next to the newly Farm Constructed Wetland. North and west of the wetland is the Rödabäck Stream which feeds the wetland. (The markers: USR, Inlet, 1-6, Outlet, P, and DSR are locations

3.2 Productive wetlands in a general context

A Farm Constructed Wetland would normally serve a multitude of purposes. It provides an opportunity for storing water locally, thus increasing irrigation possibilities while reducing flow peaks in the local stream. Wetlands also promote biodiversity since they provide a microenvironment different from the surrounding agricultural fields, on top of which they are also characterised by internal physical variation. Maybe the most important from the point of view of environmental protection, a wetland has the potential to reduce the number of nutrients leaving the farm with the excess flow out of the fields.

Since the water in a Farm Constructed Wetland is enriched in nutrients, there is an opportunity to combine the objective of reducing local and regional eutrophication with another objective: increasing farm production with no extra input of fertilisers. Such an increase in farm production could be achieved by using wetland water for irrigation. Another option would be to produce a commercial crop in the wetland itself. An extra advantage of growing and harvesting plants within the wetland is that besides using nutrients in the water body, such plants could also draw nutrients from the sediment layer, otherwise creating return flows of nutrients caused by resuspension. In fact, the temporally increasing amount of nutrients and other substances in a wetland sediment layer makes it imperative to remove such a layer after some years of operation unless it can be reduced in another way.

Growing plants to produce food or energy is thus a palatable option. However, it takes careful planning and consideration of several factors. Such aspects are:

- Suitable plants
- Demands on the operation of the wetland and possible consequences for other objectives
- Legal requirements for such activities
- Commercial aspects

Most of the aspects mentioned above must be evaluated on a case-by-case basis, considering national regulations. However, legal aspects are essentially national in character, and the suitability of plants is basically a function of geographical/climatological data.

3.3 Considerations - Swedish context

3.3.1 Edible plants

Suitable plants

As mentioned previously, most considerations in connection with growing edible crops are dependent on climatological and biological factors, which are bound by the geographical location of the farm-constructed wetland. However, below, we will start by presenting and discussing important factors which are governed by Swedish laws and how Swedish authorities normally apply them.

But first, the issue requires a definition of the term "edible crop". The list below provides examples of some plants that may be relevant in this context. We have also structured the list of potential plants according to a logical order.

- Major crop: Edible cultivated plant that can be grown on a large scale and is significant as a calorie base for humans. Traditionally, there are no routines for cultivating edible crops in water in Sweden. Rice, for example, does not fit climatically here.
- Minor crop: Edible cultivated plant that is not significant as a calorie base for humans but can be eaten.

An example of a minor crop is mannagrass or floating sweet-grass (*Glyceria fluitans* or *Glyceria notata Chevall*), which usually grows in water. Its fruits are tasty and were used in the past as manna grains. The grains available in the market today are usually made from wheat and obtained as an intermediate product during flour preparation. Mannagrass could be a possible crop to cultivate, but there is no rational way to harvest the fruits and probably no economic interest in cultivation.

- Natural alternative crop: Edible plant that is not a cultivated plant but could be used as a flavouring. Water mint (*Mentha aquatica*) is an example of an edible, perennial herb that often grows in humid environments. The plant smells and tastes strongly of mint and could be cultivated as a spice plant. However, water mint has no current cultivation history other than as an ornament in garden ponds.
- Hydroponic cultivation can: This can be briefly described as planting plants (e.g. lettuce, tomato) in plastic containers with their roots in a nutrient solution instead of soil. This form of cultivation could possibly be done outdoors in Sweden but requires complex systems for controlling nutrients, temperature, and light so that the crop does not risk being damaged if something goes wrong in the cultivation process.

Legal aspects

In cases where landowners in Sweden receive compensation for establishing a wetland, an agreement is usually drawn between the landowner and the counterpart representing the state. Normally, this would be a municipality or the local water council. In such an agreement, the landowner is committed to abiding by certain terms regarding both construction and operation of the wetland. If the agreement is violated, the landowner might forfeit the financial subsidies.

Constructed wetlands are covered by habitat protection according to the Ordinance 1998:1252 on area protection according to the Environmental Code (SWEPA, 2014). Within a habitat protection area, conducting any activity or taking any action that may harm the natural environment is prohibited. Therefore, anyone planning to conduct an activity or take action within a habitat protection area must first assess whether it may harm the natural values of the habitat. If there is a risk of damage to the natural environment, the County Administrative Board must seek a dispensation from the habitat protection regulations. If there are special reasons, a dispensation from the prohibition may be granted in individual cases.

Commercial aspects

When selling primary food products in Sweden, the requirements for registration and approval depend on how much, how often, and what is being sold. A permanent business should normally be registered. If primary products are sold in limited quantities, there is no need for registration as a food business. The County Administrative Board assesses whether registration is needed based on the scale of the operation. If sales are made directly to consumers, following national hygiene and labelling regulations may be sufficient.

For regular sales or food processing, registration as a food business is required in the stage after primary production. Approval of the company and premises used for the business is also required. The municipality's environmental and health protection office assesses whether the sale should be registered as a food business. As a registered food business, one must comply with all the requirements of food legislation, including general hygiene rules, traceability rules in hygiene regulations, and labelling and food information requirements in information regulations.

From the above discussion of the laws and regulations governing the sale of food, it can be concluded that if the sale is to be made on a large scale, there is much to consider.

There are also specific requirements for irrigation water and hygiene in cultivating leafy greens, which are relevant when the plants are grown in water. Leafy greens are foods often eaten without heat treatment and can be contaminated with pathogenic microorganisms during cultivation and harvesting. Contamination can occur, among other things, through irrigation with contaminated water or the spread of pesticides or contamination from personnel and equipment during harvesting and further handling. Guidance on how to meet the requirements of the legislation is available in "Operational goal 18 - Leafy greens irrigation water, hygiene in cultivation" (SFA, 2023).

Overall, the possibilities for selling leafy greens grown in surface water from agricultural lands, such as water mint, are limited. It is difficult to control the purity of the water. The risk of flooding and contamination of the plants is high, while the requirements of the Swedish Food Agency for irrigation water for leafy greens are high (SFA, 2023).

3.3.2 Energy crop

Suitable plants

Crops for energy production are fairly common in Sweden. The biomass is burned and converted to energy or used to produce biogas. Common types of crops in Sweden are willow (*Salix*), poplar, hybrid aspen, and pipe flange. We focus on biomass for burning, with willow being the most relevant plant in the circumstances.

Various species of willow, especially basket willow, water willow, cracking willow, and other imported species, are used for energy forestry in Sweden. Four to five years after planting with cuttings, the stand becomes about 6 meters high and can be harvested for the first time. Harvesting always takes place in the winter. After harvesting, new shoots emerge from the harvested stumps, and four years later, the stand is 6-7 meters high and can be harvested again. Willow stands estimated to be able to provide at least six harvests, which normally means 24 years of cultivation. After that, switching to other crops or perhaps to another type of cultivation is advisable.

Legal and environmental aspects

Willow cultivation is considered positive from an environmental perspective, partly because cultivation and combustion are carbon neutral and partly because the risk of nutrient leakage is minimised compared to annual crops. Willow plantations in open fields enrich the landscape and become effective shelters for birds and wildlife.

A *Salix* plantation can take up nutrients from the wetland sediments. The typical potential uptake of nitrogen was found to be 81-111 kg ha^{-1}, and the corresponding value for phosphorus was 11-15.5 kg

ha^{-1} (Rodzkin et al., 2019). These numbers, albeit for willow growing in soil, correspond quite well to annual accumulation in Swedish wetlands dominated by agricultural runoff (REAS, 2009). Typical values ranged from 50-150 kg ha^{-1} $year^{-1}$ for nitrogen and 20-40 kg ha^{-1} $year^{-1}$ for phosphorus. It is thus reasonable to assume that willow growing in a wetland would substantially reduce the need to remove sediments enriched in nutrients.

Willow cultivation is also used as a vegetation filter, where society's waste products (leachate, sewage water, sludge) are purified, primarily from nutrients but also from some heavy metals, etc. In Sweden, there are several examples of willow plantations where sewage water, after undergoing mechanical or biological treatment in the sewage treatment plant, passes through the plantation.

From a legal point of view, the energy crop has a great advantage concerning edible crops since all rules related to foodstuffs are irrelevant. And, since the willow positively affects the environment, the legal procedures should be relatively straightforward.

Commercial aspects

Compared with the case of edible crops, the legal framework surrounding the production and sales of energy crops is fairly simple. On the other hand, the profitability is not as stable as the grower might wish for. This is mainly due to fluctuating prices on the market for the fuels produced. This, in turn, depends on market prices for other types of energy commodities.

The simplified profitability calculation (Table 6) is based on the following assumptions (SBA, 2019). There are once-off costs associated with starting the plantation in year 1. After that, there are recurring costs, which are cyclical according to the harvest interval, normally 4 years. The production is estimated to last 6 cycles or 24 years. The income comes from selling the harvested dry material on the energy market. Normally, in Sweden, there is also a start-up subsidy for planting crops for energy. The harvest is sold as solid fuel with a standard calorific value of 4.4 MWh/ tonne dry matter. The harvest gives 30-35 tonnes of dry substance, slightly less for the first harvest.

There are several uncertainties in the profitability calculation. First, the unit costs/income are for 2019 (SBA, 2019). Since then, prices have increased considerably, especially in 2022-2023. Secondly, the market in Sweden for *Salix* fuel is highly localised, with effects on both fuel price and transport costs. With a plantation in a constructed wetland, using nutrients in the water and sediments, the cost of fertiliser can be reduced. However, the small margins (if any) mean that economic gains cannot be the main motivation for growing energy crops in Farm Constructed Wetlands in Sweden.

Table 6 - Simplified profitability calculation (SEK year^{-1}) for Salix plantation 1 ha (SBA, 2019). Assumptions described in the text.

Costs

Start-up cost, yr 1	Recurring cost / cyclic	Harvest costs / cyclic
1 000 SEK/yr	2 000 SEK/yr	7 000 SEK/yr (incl. transport)

Income

Fuel sales	Subsidy
11 000 SEK/yr	300 SEK/yr

Profit

Total cost	Total income	Profit
10 000 SEK/yr	11 300 SEK/yr	1 300 SEK/yr

3.4 Considerations - Gårdstånga Nygård

3.4.1 Edible crops

Demands on the operation of the wetland and possible consequences for other objectives

A constructed wetland is usually designed to fulfil a specific need or purpose, such as nutrient removal, flow regulation, irrigation, or increasing biodiversity. Often, multiple benefits are combined, and the constructed wetlands vary in hydrological conditions, size, depth, etc. If one were to explore the possibility of growing an edible crop in a constructed wetland, optimising it for that purpose would be advantageous. The targeted, older, small wetland (Lilla Skeglinge 1:1), see Figure 18, is designed as a combination wetland primarily intended for irrigation purposes.

In an irrigation pond, the water level can fluctuate during water withdrawals, which means that particularly shallow shores can be drained during the growing season. This means that the pond can be very difficult to use for growing edible crops. Additionally, because the water in the wetland is intended for irrigation, no crop that requires a lot of water can be grown there.

Legal aspects

In the case of Gårdstånga Nygård, the agreement for wetland establishment, which serves as the grounds for the financial compensation from the Swedish government, is drawn up between the landowner and Kävlinge River Water Council. In this agreement, restrictions on the use of the wetland can be noted. The landowner has committed to the following, among other things:

- The land surrounding the facility must be covered with grass and herbs. The landowner is responsible for removing trees and bushes around the inlet and outlet devices so they are not damaged by growing roots, for example.
- Within the area covered by the agreement, the landowner may not: a) plough up the land around the facility, b) spread manure or pesticides, c) plant or introduce fish, birds, crayfish, or other animals within the agreement area without permission from the County Administrative Board.
- With regard to the duration of the facility, the landowner undertakes, during the time agreed upon by the parties (20 years), not to intentionally carry out measures that may damage the facility or otherwise cause changes that negatively affect the facility's water supply or storage capacity.

If the specific wetland is to be used for growing edible crops, consideration must be given to avoid violating the agreement. For example, it must not prevent the landowner from accessing the inlet and outlet areas for maintenance. It must also be ensured that no animals accompany the planting of vegetation or that the cultivation does not dam or affect the water supply or storage capacity of the wetland.

3.4.2 Energy crops

Design and management of the wetland

At the older, small, constructed wetland, see Figure 18, which is intended for the new energy crop, willows are already growing. More specifically, they are grey willows, which are commonly found in agricultural landscapes and wetland environments in the region. When planting for experimental cultivation, it is suggested that the growing willows on the site be used as plant material to avoid introducing other (potentially foreign or invasive) species into the environment.

The rapid establishment of the plantation results in good growth and high yields in willow plantations, so it is important to choose cuttings carefully and plant them correctly. Willows are usually planted with cuttings, about 20 cm long sticks. The shoots are then allowed to grow for a few years, after which they are harvested, and new shoots are allowed to grow from the stumps.

In the first place, it is suggested that plant material be taken as cuttings on or near the site, and if for some reason this does not work, cuttings of the same species growing in the wetland can be purchased.

Before planting, soil preparation and removal of other plants should be done to facilitate the establishment of the plantation. Planting should be done on the shoreline. The cuttings are planted upright, with the top a few centimetres above the ground/sediment. For best results, planting should be done between March and June. If planting is done later, willow seedlings may have lower survival rates and poorer growth. Willow has poor weed competitiveness during the planting year. Weed control during establishment is, therefore, very important. Weed control during the planting year should be done mechanically with manpower, as chemical control in and around water is prohibited.

Cost estimate

A rough cost estimate for establishing a willow plantation at the small constructed-wetland on the property Lilla Skeglinge 1:1 results in a total cost of around 50,000 SEK. The estimate is based on planting approximately 300-400 cuttings on an area of approximately 1000 m^2. The estimate includes machinery costs, manual labour, and project coordination. The estimate does not include any costs for operation and maintenance after establishment, such as weed control, replanting, harvesting, etc. Any costs for purchasing plant materials are also not included in the estimate.

3.5 Results - water quality

3.5.1 Water Quality in the Farm-Constructed Wetland

With reference to the sampling program and elements analysed as in Table 7 (Table 7 in WATERAGRI D5.3), some selected results are illustrated in the following figures. The sampling period of this monitoring program started on 2021-06-11 and finished on 2022-11-30, with 15 samplings in total. All the analysis data are stored in an EXCEL file and will be available for WATERAGRI through the project shared folder.

Table 7 - Categories of water sampling and list of elements (analysed either on-site or in the laboratory).

Type of parameters	Analysed elements for water samples
Physical	pH, Redox, DO, TSS, Salinity, EC, Resistivity, TDS, Turbidity
Mineral	Al, As, Cu, Ni, Pb, Zn, Co, Cr, B, Cd, Ca, Fe, Mg, Mn, Na
Organic matter and nutrients	TOC, DOC, TP, TN, NH_4-N, NO_3-N, K, BOD, COD

For mineral elements: Al, As, Cu, Ni, Pb, Zn, Co, Cr, B, and Cd, the analyses show that they are either below the detection level or have concentrations in general below 0.001 mg L^{-1}. On the other hand, for Ca, Fe, Mg, Mn and Na, which are the most significant elements at the site, the variation patterns and trends are presented in Figure 20 below.

Most of the physical parameters collected have a very stable concentration level with minimal seasonal and spatial variations. The pH and turbidity show a clear variation pattern. pH has a max-min-mean value of 9.78 – 6.7 –7.79, showing a slight tendency of basicity. Variations in turbidity are mostly related to climate events such as rainfall, wind, and agricultural activities. Results also show that the pH in the summer season is higher than in the winter. For turbidity, the seasonal change is not significant. Still, there is a clear difference in those three points close to or in the river (Inlet, USR and DSR) compared to other sampling points with much larger fluctuations over the whole period. These variations are displayed in Figure 21.

For the biological and nutrients distribution and variations, the preliminary plots are also displayed in Figure 22, where the variation pattern of each parameter is clear, and the largest temporal variation is found for K, with a maximum value of up to 54 mg L^{-1}. Further analyses need to be done in relation to activities such as agriculture.

For the third group with nutrients and other indicators distributions and variations, COD and BOD_5 are among the most significant. For COD, a smooth decreasing trend spatially from upper stream to downstream and temporally during the sampling period was noted. On the other hand, no clear trend is found for the case of BOD_5. All the values found are within the safety intervals for these indicators (EU, 1998; WHO, 2017). The spatial and temporal trends of these two parameters are presented in Figure 23.

As shown in Figure 23, the smooth decreasing trend spatially from the upper stream to downstream and temporally during the sampling period can be quantified by trend analysis. It is also interesting to quantify the trend of nutrients for the wetland system for spatial and temporal dimensions. This is presented in Figure 24 and Figure 25, where linear trend analysis of TP and TN over the wetland for each sampling date is plotted together with their respective regression equations. It is hard to confirm the general decreasing trend for both TP and TN since the number of positive trends is 8 out of 15, and the negative trend cases are 7 out of 15 for TP. However, it can be seen that the slopes of the negative trends are generally larger than that of the positive. It can also be noted that the fluctuations of TP in both spatial and temporal scales are much less. It may be worth mentioning that the sampling dates (15 times over two years) are too few to provide reliable trend analysis. For TN, the number of positive trends is 7 out of 15, the negative trend cases are 8 out of 15, and the magnitudes of the fluctuations are much larger, with a maximum value over 20 mgL^{-1}. Regarding R-squared (the Goodness-of-Fit) values for each case, R^2 for TP are generally higher than that of TN, indicating a greater scatter of TN over spatial and temporal domains.

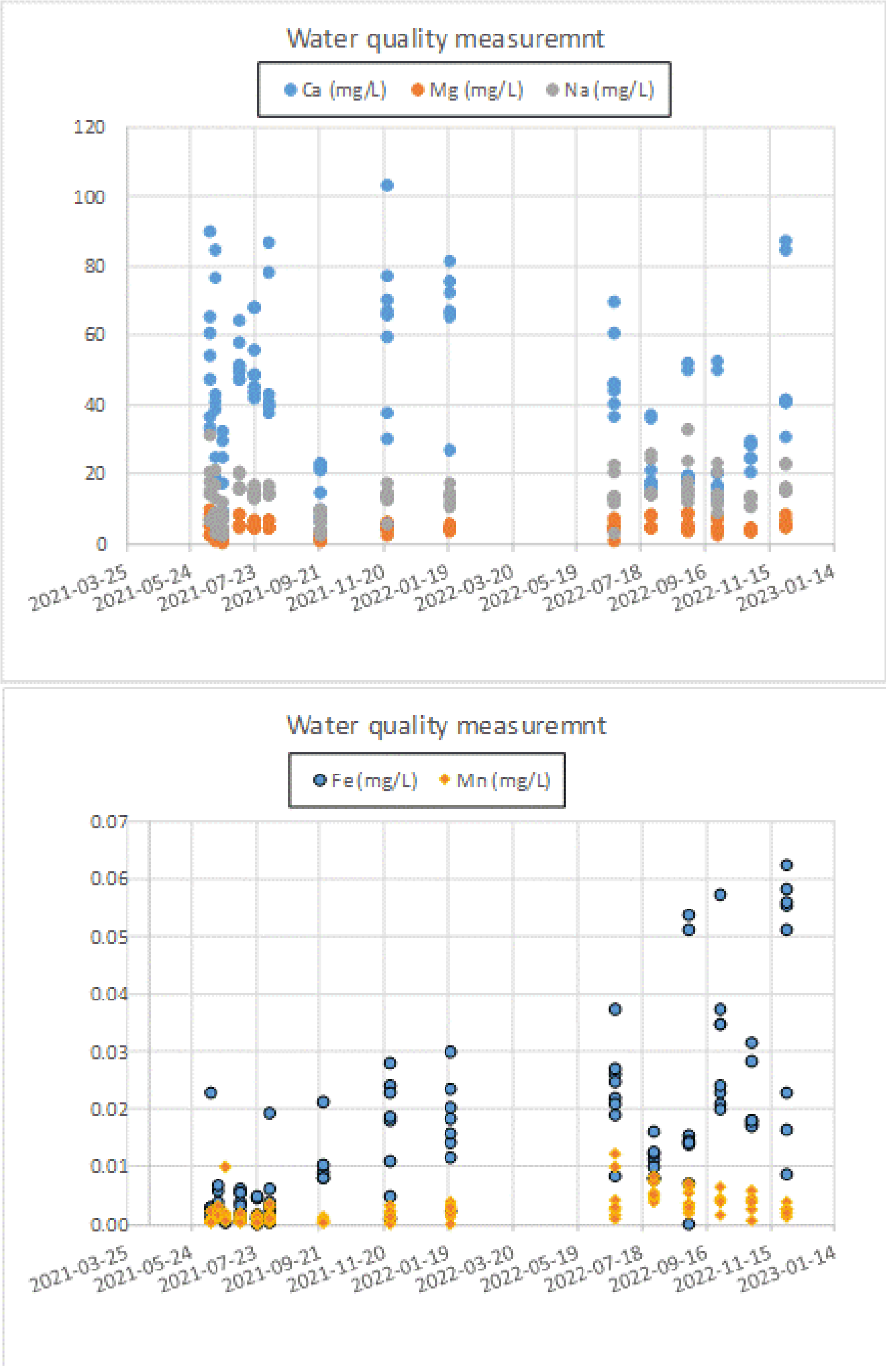

Figure 20 - Variations of selected elements during the water sampling period.

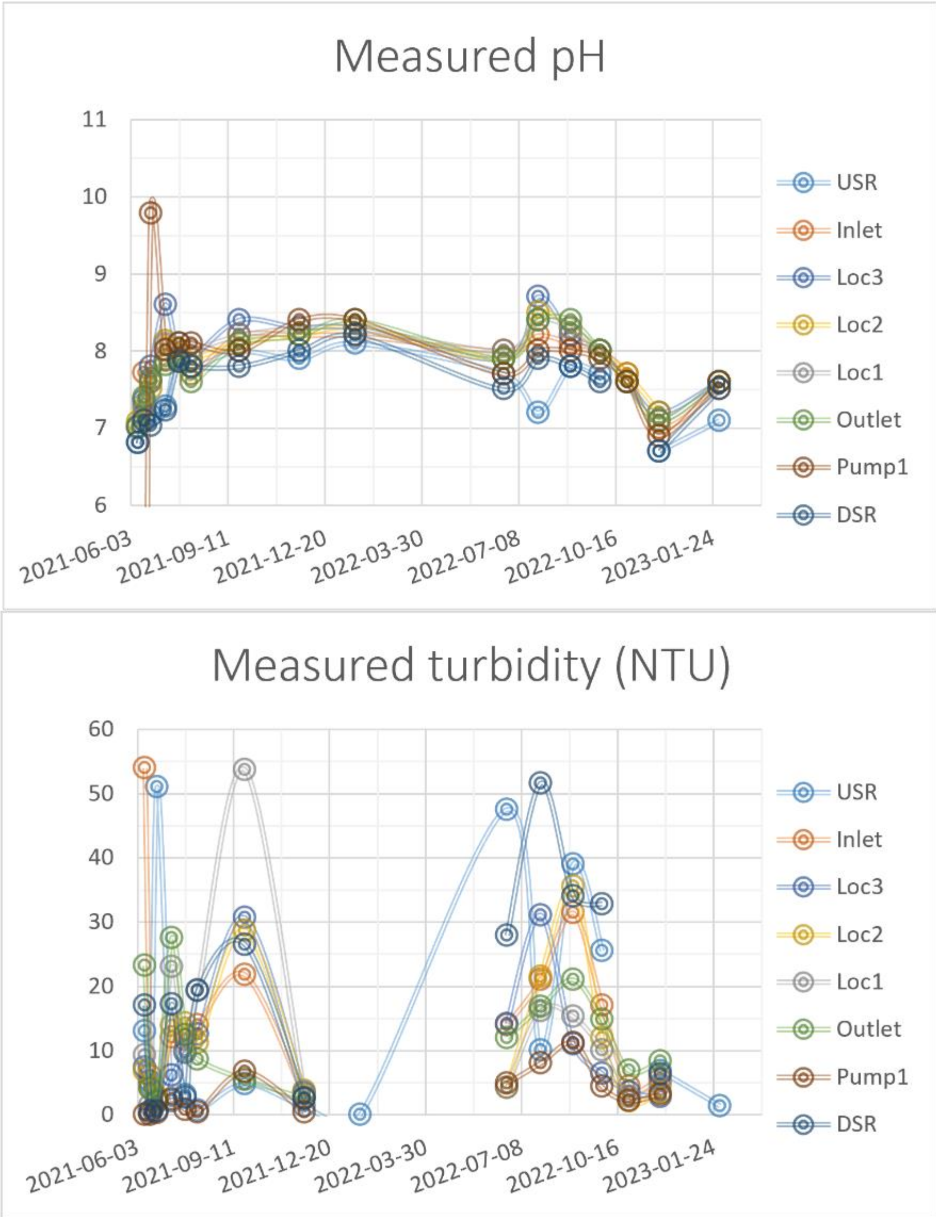

Figure 21 - Variation of pH and turbidity at different locations during the sampling period. See Figure 18 for sampling points location P = Pump1).

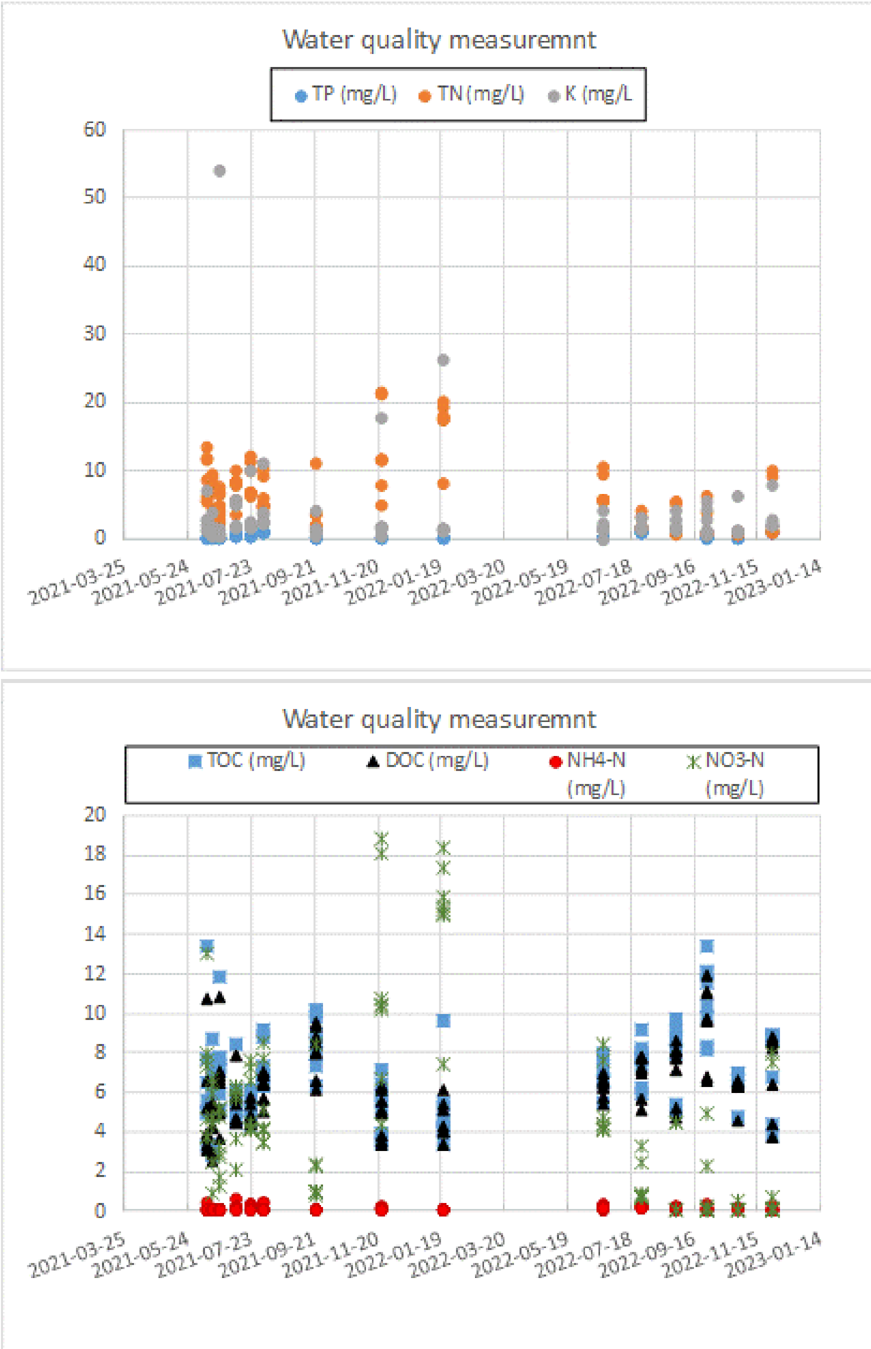

Figure 22 - Selected water quality indicators and their variations during the sampling period.

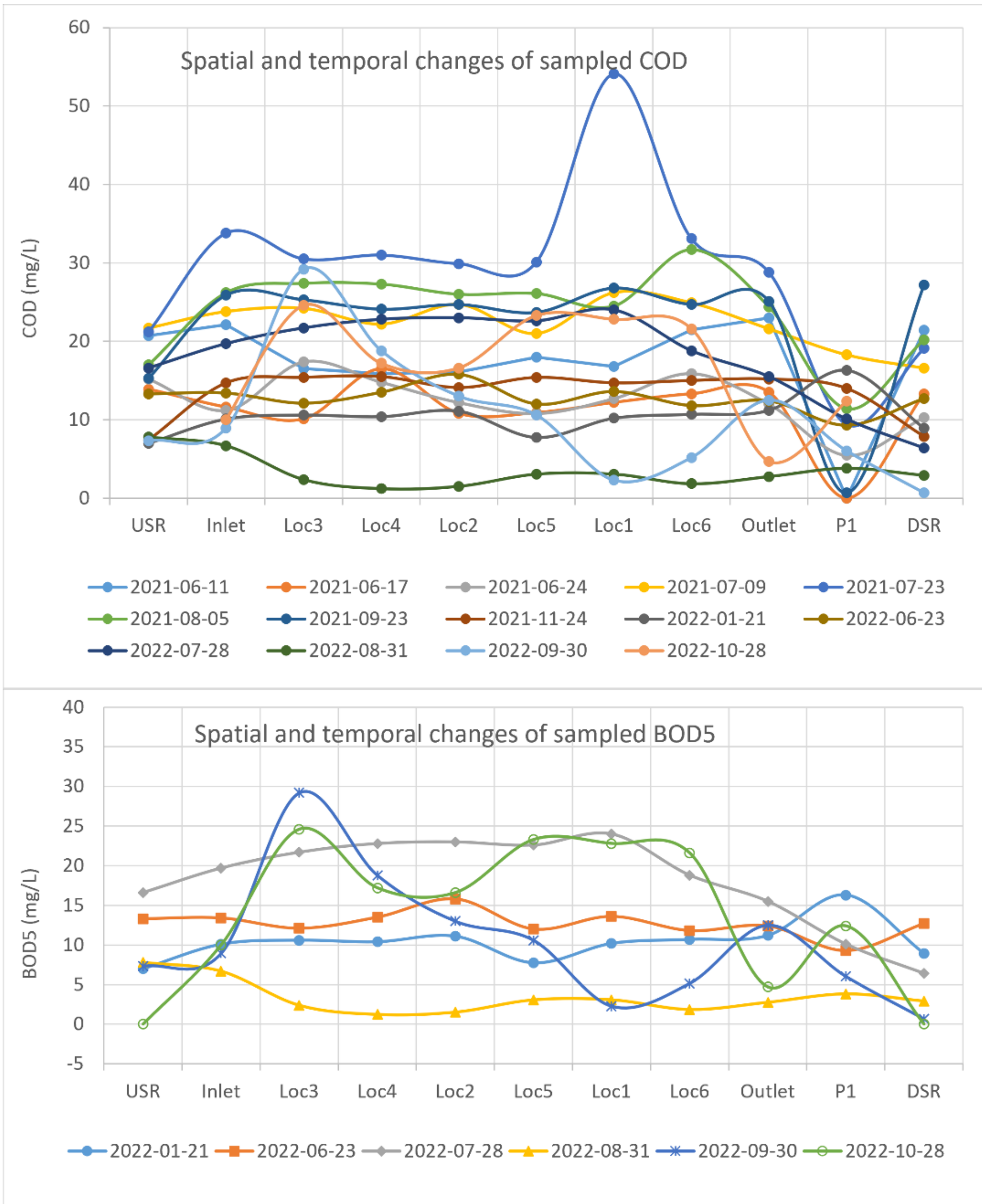

Figure 23 - Spatial and temporal trends of COD and BOD5. The horizontal axe represents most upper streams to most downstream.

Table 8 - Linear regression results for TP and TN as displayed in Figure 24 and Figure 25, respectively

Sampling date	The regression equation for TP (Figure 24)	The regression equation for TN (Figure 25)
2021-06-11	y = -0.0112x + 0.2763 R^2 = 0.7487	y = 0.9854x + 5.0916 R^2 = 0.4312
2021-06-17	y = 0.0077x + 0.2441 R^2 = 0.4906	y = -0.7154x + 9.7359 R^2 = 0.3539
2021-06-24	y = -0.0007x + 0.2289 R^2 = 0.0062	y = -0.1212x + 5.3374 R^2 = 0.0238
2021-07-09	y = -0.0276x + 0.591 R^2 = 0.512	y = -0.1212x + 5.3374 R^2 = 0.0234
2021-07-23	y = -0.0073x + 0.4388 R^2 = 0.2999	y = 0.2357x + 7.334 R^2 = 0.0578
2021-08-05	y = -0.0111x + 1.1031 R^2 = 0.4988	y = 0.0675x + 5.8795 R^2 = 0.0052
2021-09-23	y = 0.0002x + 0.2324 R^2 = 0.0057	y = 0.5655x + 0.8746 R^2 = 0.1906
2021-11-24	y = 0.0023x + 0.0575 R^2 = 0.3179	y = -0.3337x + 14.2 R^2 = 0.0196
2022-01-21	y = 0.0006x + 0.0648 R^2 = 0.0197	y = -0.6459x + 19.927 R^2 = 0.1795
2022-06-23	y = 0.0006x + 0.2077 R^2 = 0.0156	y = 0.0502x + 6.5338 R^2 = 0.0037
2022-07-28	y = -0.0025x + 1.0703 R^2 = 0.6044	y = -0.0528x + 2.4483 R^2 = 0.016
2022-08-31	y = -0.0042x + 1.0897 R^2 = 0.5467	y = -0.0181x + 2.0588 R^2 = 0.0005
2022-09-30	y = 0.0004x + 0.2281 R^2 = 0.0129	y = -0.2202x + 2.9186 R^2 = 0.0682
2022-10-28	y = 0.004x + 0.0788 R^2 = 0.5647	y = 0.0343x + 0.7247 R^2 = 0.3163
2022-11-30	y = 0.004x + 0.0788 R^2 = 0.5647	y = 0.0969x + 2.8614 R^2 = 0.0036

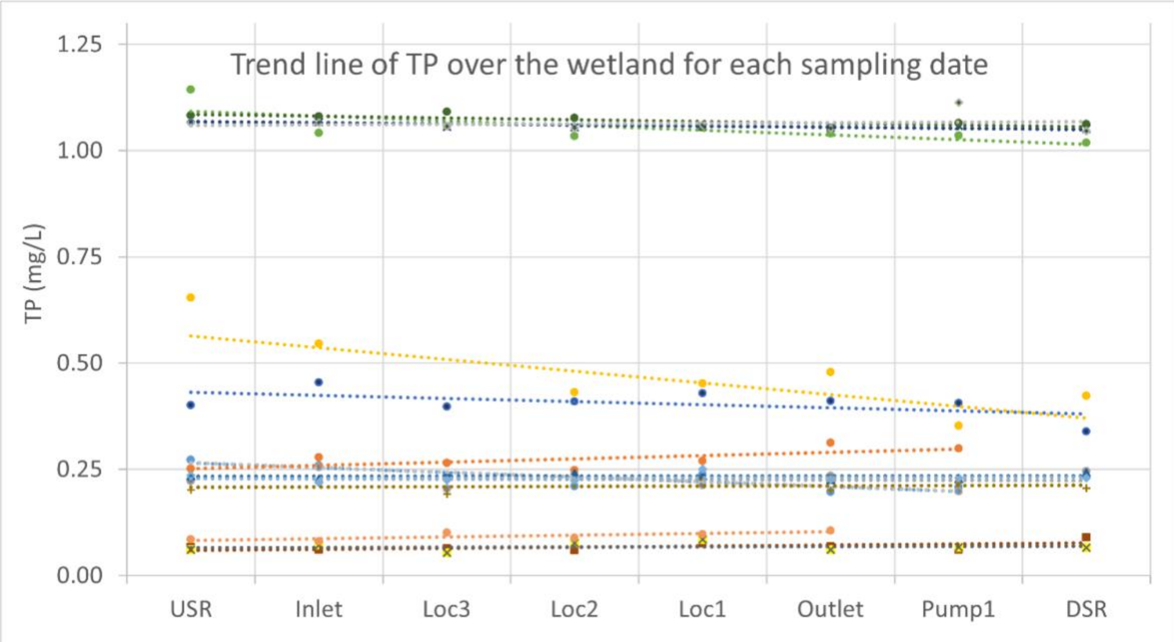

Figure 24 - Linear trend analysis of TP over the wetland for each sampling date in Table 8.

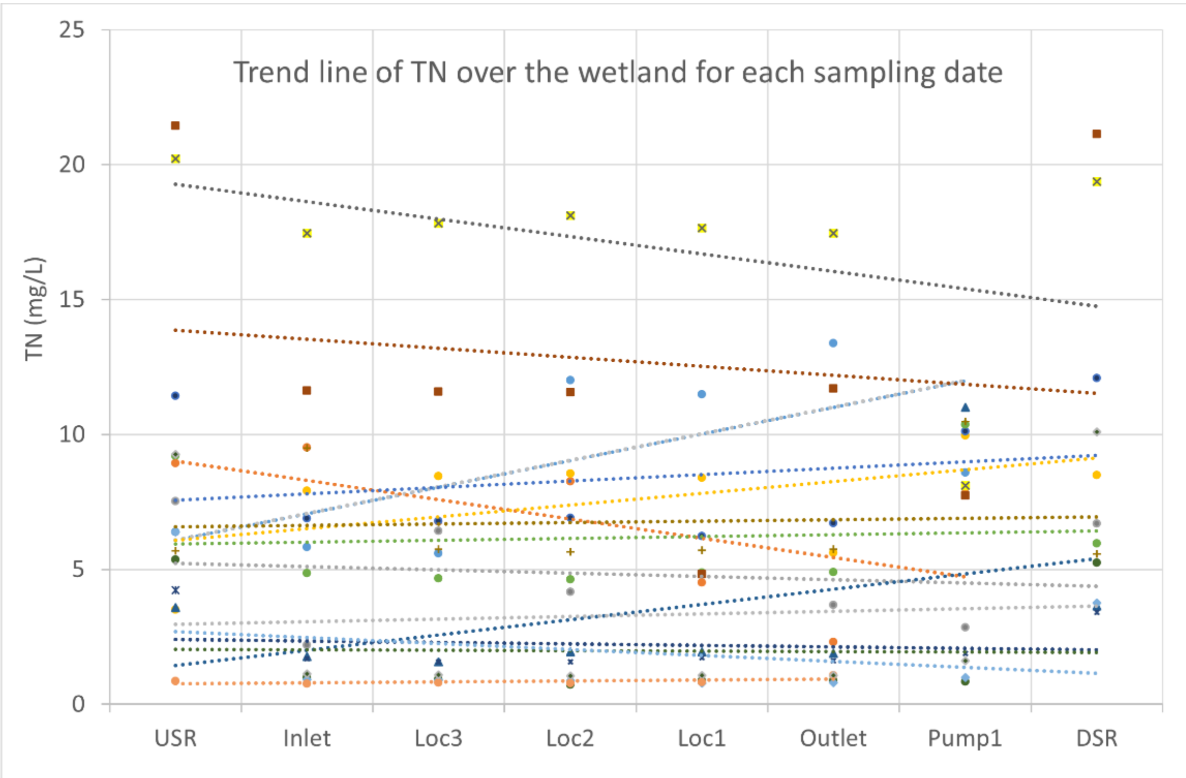

Figure 25 - Linear trend analysis of TN over the wetland for each sampling date in Table 8.

4 Bioengineering techniques for nature-based systems, biomimicry workshop, and passively aerated prototype (ALCN)

This part of the document will focus on ALCN results following Task 4.1: a) bioengineering techniques, hence suggestions on how the pilot systems investigated can be applied on a larger scale; b) the biomimicry workshop outcomes; c) the construction of a prototype with semi-passive aeration prototype.

4.1 Bioengineering Techniques for nature-based solutions

ALCN developed different nature-based systems within WATERAGRI, namely two filters that address two different situations:
a) **agricultural surface runoff** (Mistelbach, Case-study II, Austria) and
b) **subsurface drainage water** from tile drains (Gleisdorf, Case study III, Austria).
Each system has its specifications, and in this section, we briefly describe them while detailed information is given in other deliverables. Detailed information regarding the methodology and results of each solution can be found in D4.3 (Description of developed drainage technologies), nutrient retention experiments in the laboratory in D4.5 (Advanced use of biochar for nutrient retention), and case study results in D5.3 (Data collected from case studies).

First filter system

The first system is a vertical flow, multi-layer bio-inspired filter system designed to receive free gravity agricultural runoff. The systems can be vegetated or unvegetated and comprise different substrate layers to retain nutrients, water, and sediments. The treated water exits the bottom of the system, and the water can be used for groundwater recharge or irrigation purposes. On the other hand, after being saturated with nutrients, the substrate can potentially be used for N and P recovery.

Three different filter systems were tested based on the substrate type used in the main layer (Figure 26). Biochar filter was an unvegetated filter material, with a 5 cm thin gravel layer on top, followed by 35 cm biochar main layer, 10 cm gravel 4-8 mm, and 20 cm of gravel 8-16 mm in the drainage layer. Biochar was coated with $Mg(OH)_2$ during the production by Sonnenerde GmbH, Austria, to increase biochar's phosphorus retention properties. Several studies have demonstrated that substrate containing Mg, Ca, Fe, and Al elements are potential phosphorus adsorbents (Mendes et al., 2022, Canga et al., 2016, Adam et al., 2007).

Draingarden filter was vegetated; the main layer consisted of a 20 cm top layer of Drainagarden substrate mixed with biochar (5% by weight), followed by fine Draingarden substrate without compost + 10% coarse zeolite 4-8 mm, 5 cm gravel 4 – 8 mm, and 8 – 16 mm gravel in the drainage bottom part.

The soil filter was vegetated, and the main layer was composed of local soil (loamy sand) 40 cm, followed by 5 cm of gravel 4-8 mm and 15 cm of gravel 8 – 16 mm. Results are presented in Del. 4.5.

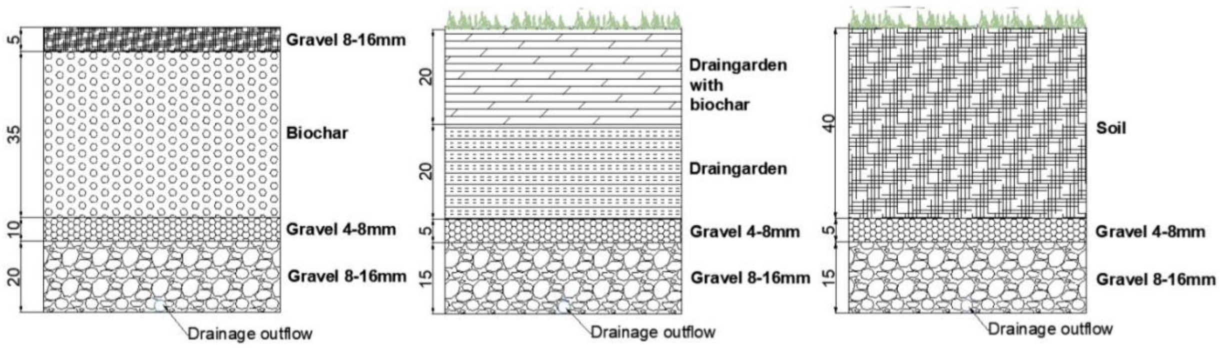

Figure 26 - Filter design of the bio-inspired filters in Mistelbach, (Austria).

As mentioned above, the Draingarden and soil filters were vegetated. The vegetation can serve multiple purposes: rain erosion protection, nutrient recovery, ecosystem diversification, or beautification. In the case of the Mistelbach prototypes, the seed mix *Bienentracht Pluss* (Bee forage Pluss) from Ackergrün GmbH was used (Table 9), which is intended to provide bee forage.

Table 9 - Seed species planted on Draingarden and soil filter systems (Mistelbach) and the biomass yield after the season 2021(*).

	Drainage filter	**Soil filter**	**Drainage filter**	**Soil filter**	**Remarks**
	1	**2**	**1**	**2**	Harvested 15.09.2021, 16.09.2021 dried for 72 hours at 70 °C
Seed species	wet weight (g)		dry weight (g)		
Trifolium pratense (Red clover)	200.4	15.9	118.4	8.5	The different kinds of clover couldn't be identified because there was no more bloom. Weight was summarised as "Clover".
Trifolium repens L. (White clover)					
Lotus Corniculatus L. (Horn clover)					
Trifolium incarnatum (Crimson clover)					
Malva (Mallow)	433.5	24.1	165	9.2	
Fagopyrum esculentum (Buckwheat)	415.4	72.8	200.9	31.0	
Camelina sativa (L.) (Camelina)	8	1.3	2	<1	
Brassica carinata (Fodder Cabbage)	29.3		12.8		

Phacelia tanacetifolia (Phacelia)	46.4	2.6	21.4	1.23	
Helianthus annus L. (Sunflower)	14.7	530.1	8.8	199.9	
Erigeron canadensis		3.8		2.1	These plants were not in the flower mixture - seeds sprouted from arable soil.
Amaranthus albus L. (Amaranth)		57.5		31.8	
Hirse		98.7		61	
Mercurialis annua (Mercurialis)		12.1		3.8	
Gramineae (Grass)		12.5		6.7	
Sum	1147.7	831.4	529.3	355.2	
Sum both filters		**1979**		**884.5**	

*Other plants advertised in the package, like *Medicago sativa* (Alfalfa), *Tagetes erecta* (Marigold), *Carum carvi L.* (Caraway), *Coriandrum sativum* (Coriander), *Lepidium sativum* (Cress), Caraway, Coriander, *Lepidium sativum* (Cress), Mustard, were not present in the harvested biomass or were not at an appropriate amount (*Foeniculum vulgare* (Fennel), hence they are not listed in the table.

After the season of 2021, the biomass collected from the two vegetated filters was harvested and weighted. The biomass was dried for 72 hours at 70 °C, and dry weight was noted. The two filters produced a dry mass of 884.53 g. Given that the area of the vegetated filters was in total 2.4 m^2, a scaled filter of 100 m^2 would yield 369 g m^{-2} and about 37 kg of total dry mass. The biomass could be used as feedstock or for other biomass conversion processes like biogas plants, feed or as raw material for other utilisation pathways (e.g., for fibre, sugars, or lignocellulosic content) to close the nutrient loop.

Second filter system

The second filter system was a horizontal flow filter prototype filled with zeolite and biochar. The multi-layer drainage filter structure was designed to be inserted in the drainage pipe and treat subsurface agricultural drainage water. The drainage filter system was developed based on site-specific parameters. Two 3-D printed structures filled with 4-8 mm zeolite and 0.5-4 mm $Mg(OH)_2$ coated biochar from cherry seeds were inserted into the subsurface drainage pipe. The monitoring plan lasted from April 2022 to September 2022 and included measurements of outflow water volume, pH, and nutrient concentrations (PO_4, NO_3-N, NH_4-N). Several iterations of 3D structures were printed before arriving at the final prototype design (Figure 27).

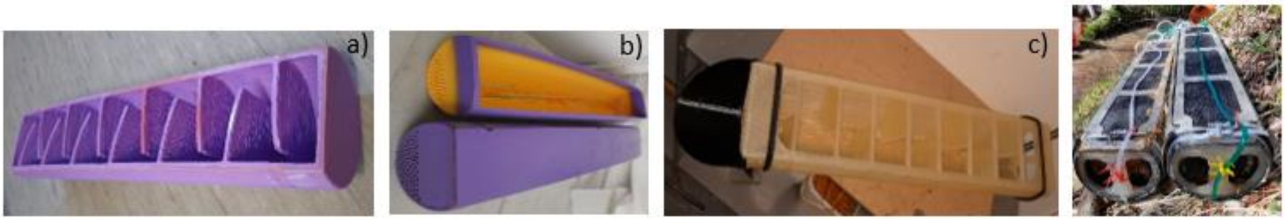

Figure 27 - Iterations of structures tested (a, b) until the final design (c), developed by alchemia-nova (ALCN).

Bioengineering techniques in field applications

Bioengineering is a collection of techniques that use biological and mechanical interventions to stabilise soil and rock. It is commonly used along river banks and slopes to control erosion, protect soil and stabilise slopes using mostly local vegetation or a combination of vegetation and construction materials. Apart from fulfilling these structural functions, bioengineering techniques also contribute to the aesthetics and biodiversity of the landscape. Bioengineering is typically a low-cost and low-tech intervention that does not need big machinery for building and has a long lifespan. Besides technical structures, bioengineering structures have an initial low structural integrity but reach and maintain high stability after a certain growing period.
In the context of the ALCN tech developments within WATERAGRI, several bioengineering techniques are recommended as accompanying measures to guide runoff water towards the filter system and protect and stabilise the systems to retain and increase filtration.

The recommended techniques include:

Crib Wall

A Crib Wall is a structure made from dead wooden logs (stretchers in the direction of flow and headers perpendicular to it) intercropped with live *Salix*. It can be implemented to secure steep riverbanks and to create guiding structures for water pathways.

Fascine

A Fascine is a bundle from live *Salix* branches with a 30-40cm diameter that protects slopes from being eroded by a passing stream or, together with the earthworks, guides water towards a specific direction.

Brush Mattress

A Brush Mattress is a superficial structure from live *Salix* branches protecting a slope in a more planar manner. This structure can also create space for increased infiltration and water storage.

Willow Hurdle

A willow hurdle is a simple woven fence kind of structure made out of dead wooden poles interwoven with live *Salix* that can be used on many occasions, like guiding water or stabilising the border of the filter system.

Proposed bioengineering techniques are perfect combinations for investigated agricultural bio-inspired multilayer filter systems (Mistelbach and Gleisdorf)

Agricultural runoff from slopes can lead to water body eutrophication, which can have significant environmental repercussions. To alleviate this issue, a filtration system at the slope's base can be erected to catch and retain runoff. This filter system can be configured to function as a drainage strip and a nutrient adsorption device.

In the case of the surface runoff filters developed for Mistelbach, bioengineering would be used as a frame that guides the surface runoff to the filter, pre-filters it through sedimentation, stabilises the boundaries of the filter, and prevents the filter from being washed out. Out of the manifold bioengineering techniques, for example, fascines and brush mattresses would provide these functionalities so that the final setup would look like in Figure 28.

The filter system comprises an in-situ filter material that can absorb nutrients from runoff. The filter material is mainly biochar, a carbon-rich substance made by roasting organic material without oxygen. Biochar has a high surface area and porosity, making it a potential nutrient adsorbent for nitrogen and phosphorus. The filtration system can be planted with appropriate plants or left bare. Plants can help stabilise the soil and give additional nutrient uptake if grown. The filtration system near a river can be strengthened with a Krainer wall to prevent erosion and support the structure.

The biochar adsorbs nutrients in the runoff when it enters the filter system, preventing the eutrophication of water bodies downstream. When the biochar has reached maximal nutrient retention capacity (if hydraulic challenges do not show up), it can be placed onto the field to recover the nutrients. This not only prevents nutrient contamination but also delivers nutrients to the crops.

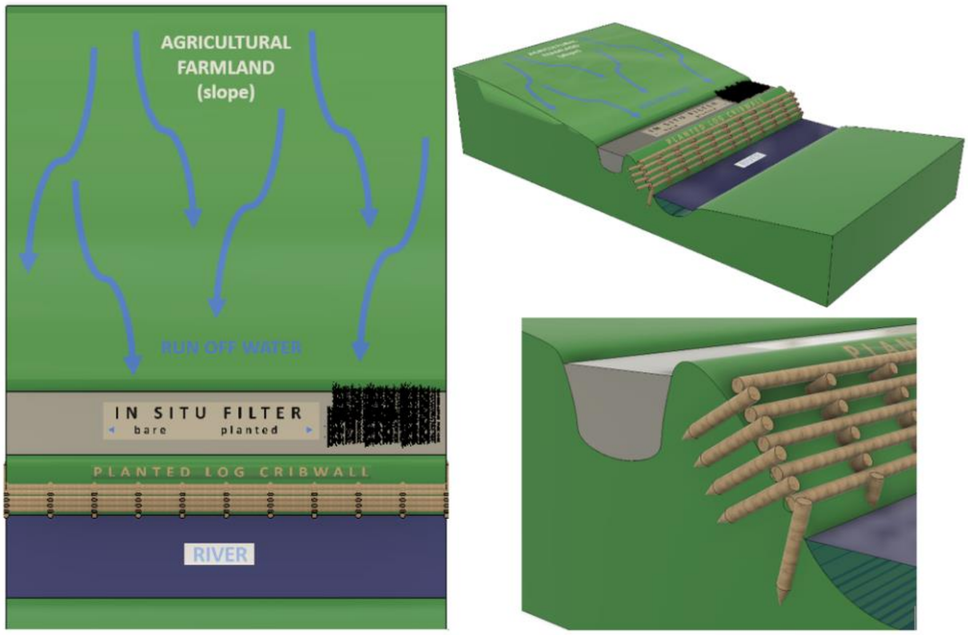

Figure 28 - Simple sketch for bioengineering techniques addressing agricultural landcover runoff in actual scale applications, alchemia-nova (ALCN).

In many cases, surface water runoff is also directed away in small hollows on the side of the field, where the last barrier before runoff could again be a longer vegetated filter strip acting as a bioswale filter, strengthened with fascines or a willow hurdle.

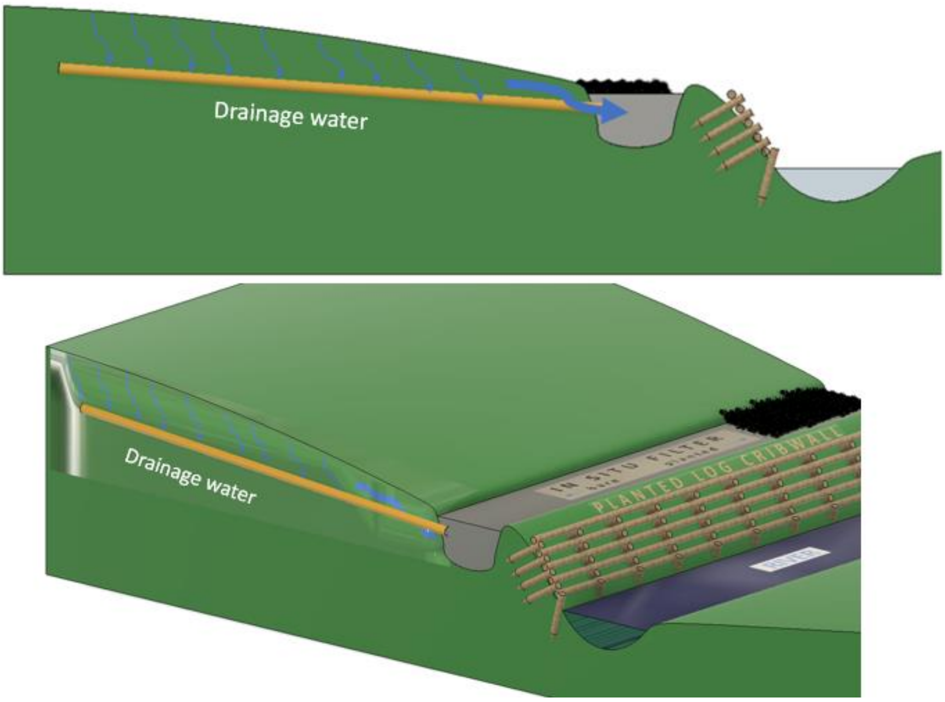

Figure 29 - Sketch for bioengineering techniques addressing subsurface drainage water in real-scale applications, alchemia-nova (ALCN).

The filter system must be maintained and monitored regularly to ensure effective operation. It is advised that the biochar capacity be routinely checked and replaced as needed. Plants, if present, must also be cared for to ensure their health and effectiveness.

If a subsurface drainage filter system such as the one for Gleisdorf is developed, bioengineering techniques are presented in Figure 29. A brush mattress could be used to stabilise the boundary of the filter, and a crib wall to stabilise the riverbanks.

To summarise, the agricultural runoff filter system is an excellent option for preventing nutrient contamination and eutrophication of water bodies. Using biochar as an adsorbent material enables nutrient recovery and adds value to agricultural produce. Adequate maintenance and monitoring are required for the filter system to perform correctly over time.

4.2 Biomimicry design workshop for semi-passive aeration of constructed wetlands

Passive and semi-passive aeration systems

Passive aeration systems refer to natural processes that provide oxygen to the soil, water, or other environments without using energy-intensive mechanical aeration equipment. Passive aeration is achieved through various methods, including wind, water flow, and temperature changes, which create conditions that promote air exchange.

One example of passive aeration in nature is the aeration of soil through the roots of plants. As plants absorb water and nutrients from the soil/substrate, they also create a network of channels and pores that exchange air and gases between the soil and the atmosphere. This process helps maintain the soil's health and fertility and supports plant life's growth and survival.

Another example of passive aeration in nature is the aeration of water through wind-driven currents and waves. As the wind blows over the surface of a body of water, it creates currents and waves that help to mix the surface waters with the deeper waters. This process helps maintain the health and balance of aquatic ecosystems by providing oxygen to aquatic plants and animals and removing pollutants and other waste materials from the water.

A third example of passive aeration in nature is the aeration of soil and water through temperature changes. As temperatures fluctuate, they cause the air in soil or water to expand and contract, leading to the exchange of air and gases. This process can help maintain the health and balance of soil and water systems by providing oxygen to bacteria, fungi, and other microorganisms essential for the decomposition and cycling of nutrients.

Overall, passive aeration systems play a critical role in the health and balance of natural systems by providing oxygen and other essential gases and removing waste materials and pollutants. By understanding the principles and processes of passive aeration, we can design and implement systems that support the health and sustainability of our environment.

Biomimicry Workshop

ALCN organised a two-day biomimicry design workshop to explore integrating a passive or semi-passive aeration system into a constructed wetland system. The workshop was attended by a diverse group of practitioners, engineers, mechanics/artisans, biologists, students, and professors, all working together to develop a new and innovative aeration system. The participants were affiliated with forefront wetland company IRIDRA (1 person), the University of Natural Resources and Life Sciences of Vienna (BOKU) (2 persons), and alchemia-nova GmbH (8 persons).

The workshop was conducted under the principles of biomimicry and aimed to harness the natural processes and properties found in nature for the better aeration of the water and substrate in the constructed wetland system. To this end, the workshop participants explored the use of natural processes, such as convection and the Bernoulli effect. They considered the use of energy generation through temperature differences, such as Stirling engines and fan blowers.

Results and discussions

After two days of intensive collaboration and brainstorming, the workshop participants reached a consensus on a wetland concept that would use various principles, as shown in Figure 30.

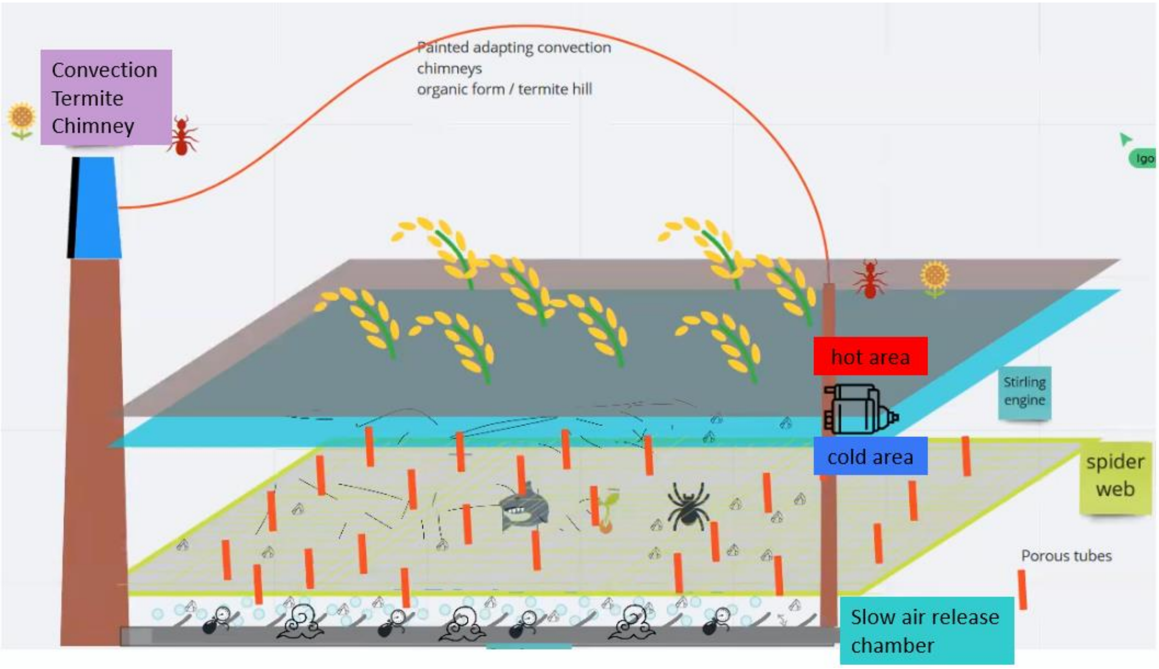

Figure 30 - The output of the biomimicry workshop in the form of a wetland concept drawing.

The concept of a passive aerated constructed wetland includes a solar chimney, clay tubes for aeration, spider web-like structures to retain air bubbles, a steering engine of mechanical aeration, and many more ideas. After a practical analysis, The solar chimney was seen as having the highest potential for both testing and implementation, and the workshop participants decided to build a prototype based on this concept.

The outcome of the biomimicry workshop was a new and innovative concept wetland that uses natural processes and properties to enhance the treatment efficiencies and robustness/resilience of the constructed wetland system. The prototype aeration system, based on the solar chimney, was developed using the input from all workshop participants and represents a significant step forward in using nature-based solutions for environmental management and sustainable water treatment.

4.3 An integrated prototype aeration system

Here, we present the design and construction of a passive integrated aeration system prototype for wetlands that uses a solar chimney effect. The prototype was designed to use the sun's energy to drive air through a vent and provide aeration to the substrate. The technical information and results of the prototype are also presented. The results indicate that the prototype effectively provided a certain airflow through the substrate, potentially increasing oxygen levels in the water column and improving the water quality of the wetland environment. This prototype concludes that the solar chimney effect poses a viable option for providing aeration to the wetland environment.

Design of the system

The prototype consists of a perforated tube placed horizontally across a substrate. The perforated pipe is connected to one lower end to provide unrestricted airflow. This end is for the experimental determination of the effect of the solar chimney and can be neglected in real applications. On the other side of the perforated tube, the solar chimney erects about 120 cm out from the representative constructed mini wetland (Figure 31 and Figure 32). The mini wetland is represented by a heavy-duty rubber box containing a granular substrate. This height over the pipe of the substrate, representing the wetland aquifer, is incrementally increased to observe the performance of a solar chimney in terms of the air exchange rate in correlation to changing aerodynamic resistance. The chimney is painted black and run by 2 LED lamps imitating the sun's radiation and causing the air movement. Once the chimney is operating, the lower inlet can be closed, and the airflow happens through the substrate into the perforated tube out through the chimney. It should be noted that the airflow is from up to down compared to common aerated wetlands where the bubbles rise through the water body up.

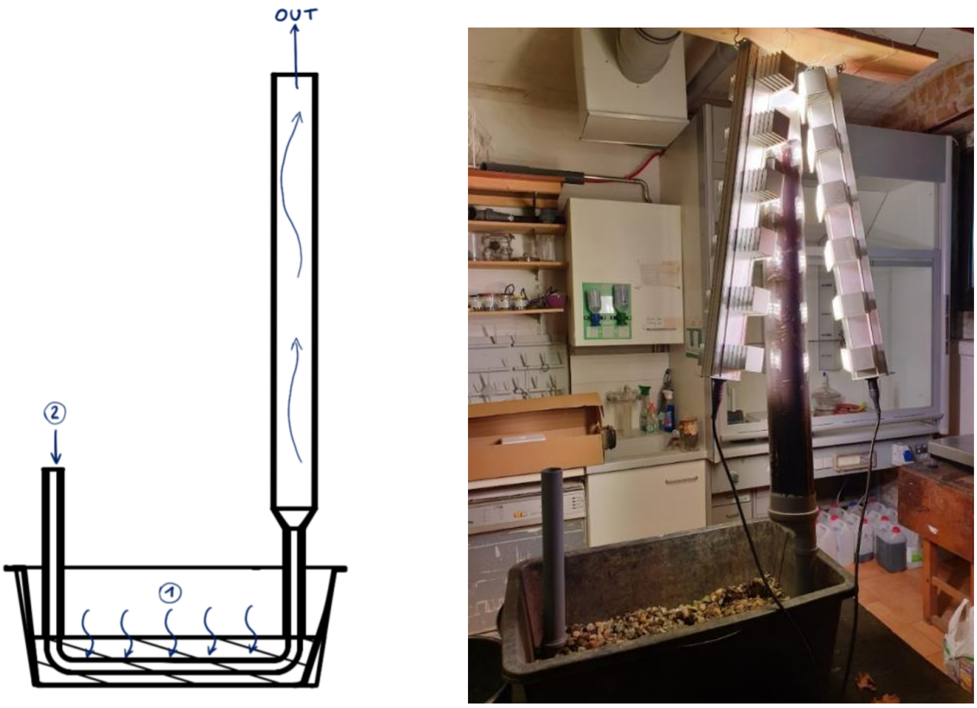

Figure 31 - The sketch shows the air movement through the piping and the substrate where (1) resembles the intended use case and (2) is for control purposes during the experiment.

Technical information

The 110 mm in diameter chimney was painted black, and the uppermost point stood 1250 mm out from the container. The area of the substrate is approximately 0.25 m² (740x340 mm container). The perforated tube has 94 holes, each drilled with a 5 mm drill.

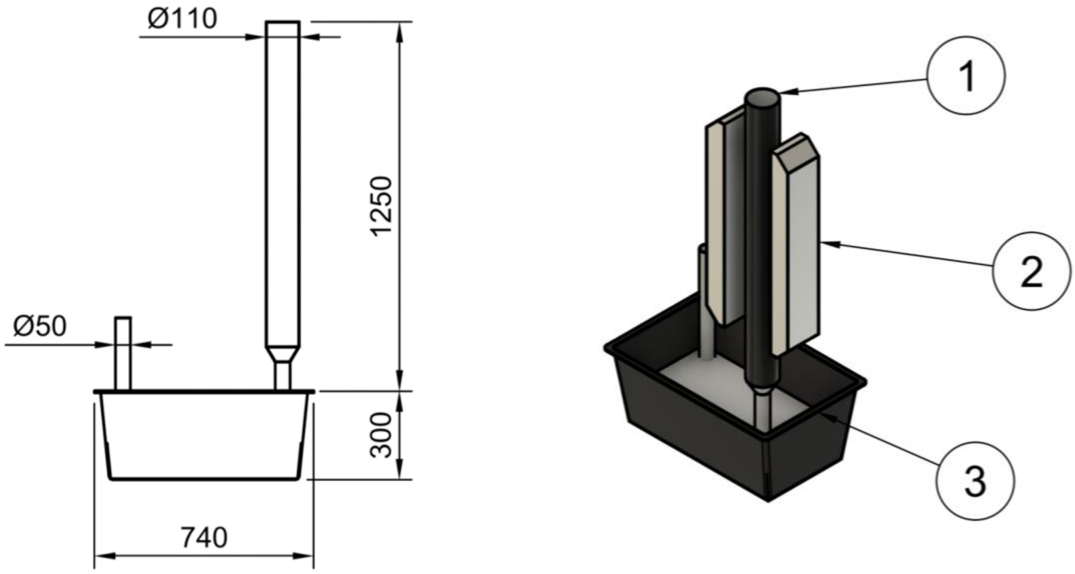

Figure 32 - Measurements of the prototype setup with the assembly showing the piping with chimney (1), the lamps (2), and the substrate with the box resembling the constructed wetland (3).

The lamps are distributed by S*ANlight GmbH* and are LED modules labelled as Gen2 S2.1 PQ6WXDSB with power consumption rated at 245 W each. The distance between the solar chimney and the lamp is approximately 5 cm. In use are two units of lamps. Noteworthy is that the light spectrum of LEDs is different from the light spectrum of the sun since the lamps are used for plant growth. The lamps are rated with the following characteristics (Figure 33).

The first phase of testing of the solar chimney aimed to determine the relationship between the thickness of the substrate and the airflow through it. The tests were carried out by gradually increasing the substrate thickness in steps 12 cm, 16 cm, 20 cm, and 24 cm. The tests were performed using an anemometer to measure the air velocity in the conducting pipe. The thickness of the substrate was gradually increased in the steps mentioned above, and the air velocity was recorded at each stage.

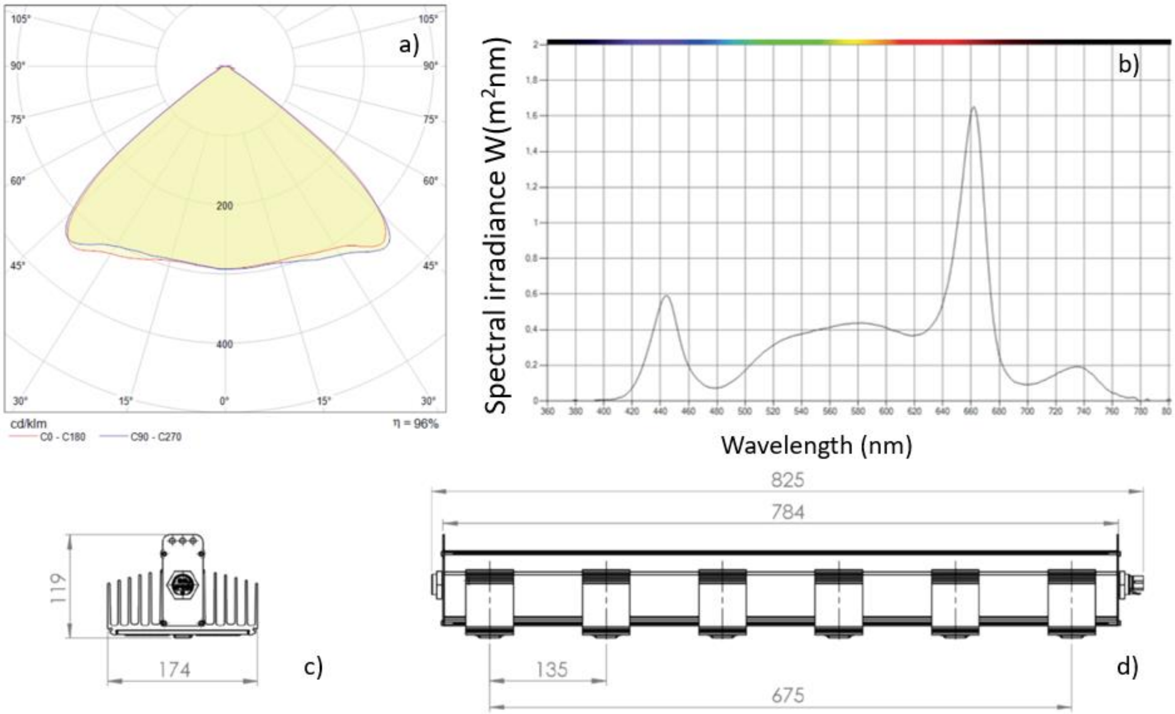

Figure 33 - Radiation pattern (a), light spectrum (b), drawing of LED lamps simulating the sun in the prototype (c, d).

Results and conclusions

The first set of tests showed a strong correlation between the substrate thickness and the air velocity through it. As the substrate thickness increased, the air velocity decreased, reaching a minimum at the highest substrate thickness of 24 cm. The results of the tests are summarised in the following graph (Figure 34), which shows the relationship between a substrate thickness and air velocity:

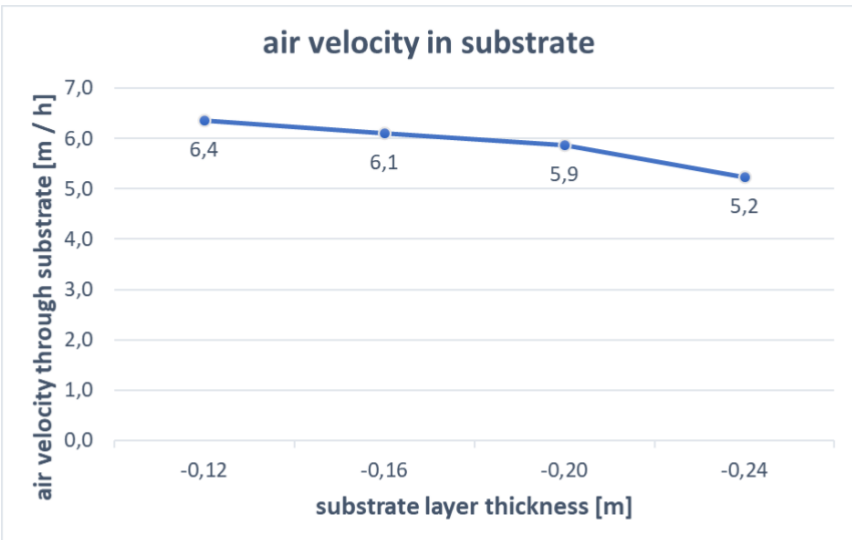

Figure 34 - Air velocity in the substrate with dry conditions and increasing soil thicknesses.

The results of the first phase of testing of the solar chimney substrate thickness show a clear correlation between the thickness of the substrate and the air velocity through it (Figure 34). As the substrate thickness increases, the air velocity decreases due to higher aerodynamical resistance, from 6.4 m h^{-1} at the lowest substrate thickness (12 cm or 0.12 m) reaching a minimum (5.2 m h^{-1}) at the highest substrate thickness (24 cm or 0.24 m) tested. These results provide insights into the design and optimisation of the solar chimney and can be used to inform future tests and improvements to the system. Figure 35 shows the extrapolated dataset of the possible air velocities in different depths. The literature on air velocities for the aeration of wetlands suggests about 0.6 m^3 m^{-2} h^{-1}. Air velocity, in this case, refers to the definition of the air volume by the surface area by time. A linear and polynomial extrapolation shows depths of 0.4 m to 0.7 m with the experimental setup that would still be covered by the passive solar chimney aeration (Figure 35). It should be noted that the airflow is only given for non-aerated saturated. Because of the suction nature of this aeration approach, the uniformity of the airflow is estimated to be better than the punctual aeration by active aeration, making it reach more parts of the substrate.

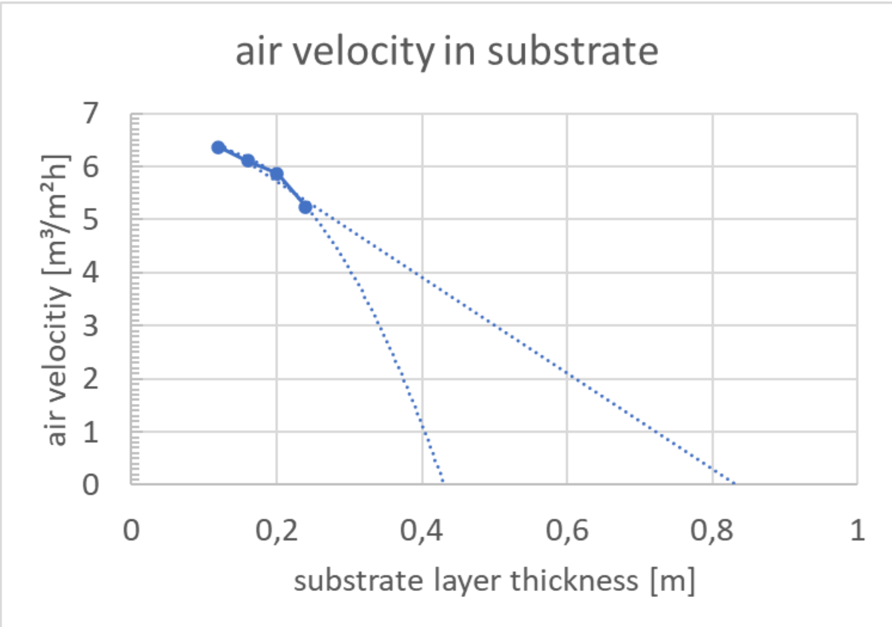

Figure 35 - Measurements of air throughput (velocity) extrapolated and decreasing with depth.

Table 10 are summarised the advantages and disadvantages of the system. The solar chimney presents an energy-efficient, low-cost option for passively aerated constructed wetlands. It relies on natural convection to create a pressure difference for air exchange, promoting even air distribution throughout the wetland substrate. This can help to improve treatment efficiency while reducing environmental impact. One of the main advantages of the solar chimney is its simplicity, as it does not require complex mechanical components and has low maintenance requirements. However, the effectiveness of the solar chimney may be limited for water-saturated constructed wetlands (i.e.

horizontal subsurface flow constructed wetlands) due to the low-pressure difference produced by the chimney, which may not be sufficient to create adequate airflow.

Table 10 - Advantages and disadvantages of the passive aeration prototype.

Pros	Cons
○ Reduced energy consumption and costs	○ Relies on external factors such as solar radiation and wind
○ Minimal noise impact	○ Potential for reduced aeration efficiency in saturated wetlands
○ Even distribution of air through the substrate	○ Limited control over the aeration rate
○ Potential for enhanced ecological function	○ Clogging of the suction pipe during saturation
○ Potential use of existing drainage pipes as aeration pipes to reduce material use	○ Requires careful design and placement of suction and drainage pipes
○ Low maintenance requirements	○ May require additional testing and analysis to determine optimal performance

By continuing to explore and develop new technologies, we can work towards finding more efficient and sustainable solutions for a wide range of challenges, including those related to water and air management. It is also essential to remember that while a solar chimney may not be the best solution for every situation, it can still have a role to play in certain circumstances, particularly in areas with high levels of sunlight and low air resistance.

5 Conclusions

Task 4.1 of the WATERAGRI project studied different types of wetlands, showing the benefits they can provide in the agricultural setting. In this deliverable several bio-engineering techniques were explored and proposed for an agricultural bio-inspired multilayer filter systems that can use biochar or other reactive filter materials inside the land and vegetation that can enhance nutrient retention from surface or subsurface agricultural waters.

Two full-scale farm wetlands were studied in Italy and Sweden, showing their positive impact on water quality. These wetlands could remove considerable quantities of nutrients and other contaminants from irrigation and drainage water, contributing to the overall water and environmental quality and the sustainability of agricultural production. An Italian system was also monitored from a volumetric aspect for 30 months, showing water fluxes dynamics that could be used for better management of the wetland.

Due to the presence of different elements useful for plant growth, the possibility of using wetlands for crop production was evaluated. The preliminary analysis for a Swedish farm wetland has shown that edible crops might not be suitable but that energy crops (e.g. willow trees) could be a good alternative, even though a business model and consideration of legal aspects are needed beforehand.

Another option for the circularity of the wetland systems and the use of biomass produced could be compost production and its later use as a soil amendment, enabling nutrient reuse for agricultural production. A study performed in Italy has produced three compost types, also mixing the plant biomass with other agricultural by-products (i.e. potato cutting, digestate). The compost produced has shown an important nutrient content, but further analysis involving other materials is recommended.

A pilot plant based on wetland technology was constructed in Italy and used to test different types of wetlands and the addition of biochar as a substrate. A horizontal flow system has shown a better removal efficiency than a surface flow system, which can be connected to the first one's better filtration and adsorption properties. Moreover, biochar was shown to be able to adsorb nutrients present in agricultural drainage water, and therefore its addition to a pilot wetland substrate was tested. Although it has shown a certain advantage, further tests would be needed to find the optimum volume mixture.

Moreover, a biomimicry design workshop was organised in Austria to explore integrating a passive or semi-passive aeration system within a constructed wetland system, an aeration type that does not require energy, and airflow results can be used for further improvement of the system. The workshop outcome was a new and innovative concept wetland that uses natural processes and properties to enhance the treatment efficiencies and robustness/resilience of a constructed wetland. The prototype of a passive aeration system, based on the solar chimney, was developed using the workshop input and represents a significant step forward in using nature-based solutions for environmental management and sustainable water treatment.

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