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EU Horizon 2020 Research for A Sustainable Future: INNOQUA—A Nature-Based Sanitation Solution

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Abstract: This paper explores the experiences of partners in the multi-national, EU-funded INNOQUA project, who have developed and are currently demonstrating the potential for novel nature-based, decentralised wastewater treatment solutions in ten different countries. Four solutions are under investigation, each at different Technology Readiness Levels (TRLs): Lumbrifilter; Daphniafilter; Bio-Solar Purification unit; UV disinfection unit. An overview of the solutions is provided, along within data from pilot sites. The project is currently entering an intensive demonstration phase, during which sites will be open for visits and act as the focus for training and dissemination activities on sustainable wastewater treatment. Barriers to market for nature-based solutions are also explored.

Keywords: nature-based; decentralised; sustainable; earthworm; daphnia; micro-algae; UV disinfection; solar purification

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1. Context

Whilst the need to provide access to safe and sustainable sanitation is pressing, there is increasing recognition that solutions cannot always be based on conventional sewer-based systems. Challenges such as the lack of stable electricity supplies, spare parts and suitably-trained operators all indicate a preference for nature-based, decentralised approaches. Such approaches can also avoid chemical dosing and be adapted to meet local treatment requirements (be they for greywater, blackwater or faecal sludge).

Decentralised solutions can be configured to remove or manage nutrients—particularly where urine and faeces are separated—but retention of the nutrients within the treated wastewater can be advantageous for irrigated agriculture in water-constrained locations. Even where logistical challenges are not present, nature-based solutions can provide low-cost sustainable wastewater treatment within both rural and urban areas—whilst complying with discharge and reuse standards.

The percentage of the EU population connected to centralized wastewater treatment systems ranges from 51% to >99%, depending on the country [1]. Although obligated to provide centralised wastewater collection and treatment for 'agglomerations' of >2000PE (Population Equivalent) under the Urban

Waste Water Treatment Directive [2], more than half the European population lives in rural areas [3] where collective wastewater treatment may not be obligated, but where other drivers—such as the need to protect the water environment—mean that decentralised treatment is necessary. Many commercial systems are already available to meet this market need, including septic tanks, small package plants and reedbeds. However, there are other emerging—nature-based—solutions that could deliver robust secondary or tertiary treatment at lower cost.

The World Health Organization estimates that, globally, up to 2.0 billion people do not have access to any form of basic sanitation (such as toilets or latrines) and that almost 700 million people are forced to defecate in the open [4]. Furthermore, in water-constrained areas, wastewater is commonly used for irrigating food crops—the WHO estimate that up to 36 million hectares of agricultural land in peri-urban areas are irrigated with untreated wastewater [4]. Climate change is also forcing governments in the Global North to consider options for water re-use [5].

It is within this context that the INNOQUA project was conceived—to demonstrate the potential of decentralised, nature-based, modular units that are capable of delivering cheap and sustainable wastewater treatment that is sufficient to meet environmental discharge standards and (where required) standards for water re-use. This paper outlines the field-scale demonstration phase of the project, which was developed from the findings of prior replicated scientific research at laboratory and pilot-scale undertaken by the National University of Ireland Galway and the University of Girona.

2. Project Overview

The key aim of the INNOQUA project is to integrate individual modular, low-cost, sustainable and biologically-based water treatment and reclamation technologies in configurations matched to local contexts in target markets: EU (France, Ireland, Italy, Romania, Scotland, Spain), Ecuador, Peru, Tanzania, Turkey and India. INNOQUA uses four treatment technologies—Lumbrifilter (LF), Daphniafilter (DF), Bio-Solar Purification (BSP) and Ultraviolet (UV) disinfection—which can be combined in different configurations to suit local conditions. System operation is remotely monitored and managed by a monitoring and control unit (MCU) that receives and processes data in real time from probes measuring (for example): dissolved oxygen (DO), conductivity (salinity), oxidation-reduction potential (ORP) and pH. An illustration of the complete system is provided in Figure 1.

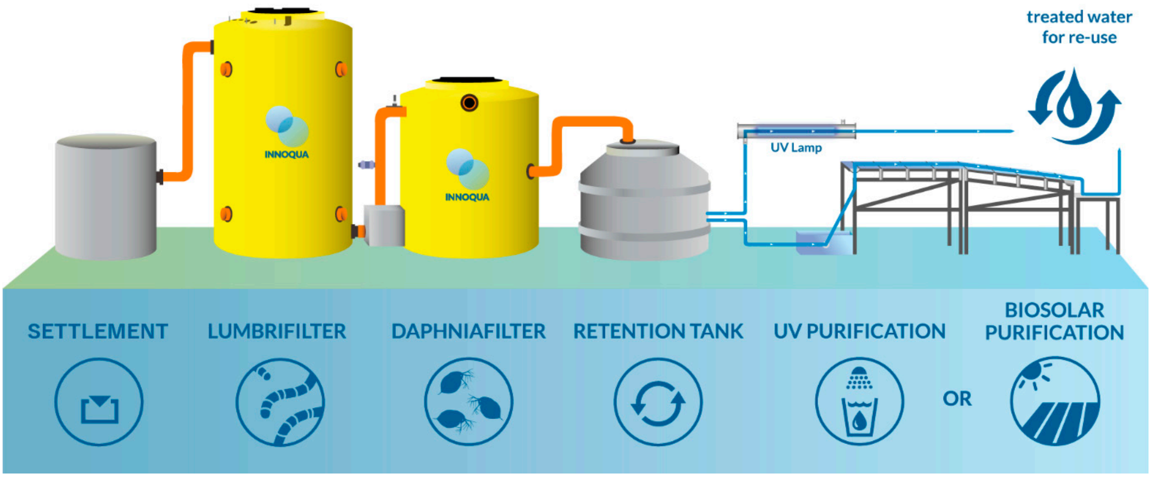

Figure 1. INNOQUA system overview. Tanks may be surface-mounted or buried, depending on site-specific circumstances.

2.1. *Lumbrifilter*

Earthworm-based solutions such as vermifiltration, 'microbial-earthworm ecofiltration' and 'Tiger toilets' have previously been shown to be effective in wastewater treatment applications, with earthworms consuming organic matter and reducing sludge accumulation rates. Earthworm activity within surface layers also helps to maintain percolation and aeration within biological filtration systems [6–9]. These principles are applied within the Lumbrifilter. This comprises a sequence of organic and mineral layers, the former hosting a population of epigeic earthworms native to the region in which the system is deployed. *Eisenia* species are typically used. Within the filter, soluble organic matter is biologically decomposed by bacteria while earthworms consume both biomass and particulate organic matter. While the Lumbrifilter does not specifically require suspended solids to be separated from wastewater prior to treatment, this can be necessary to manage sludge production from higher loads and provide flow balancing in certain cases.

2.2. *Daphniafilter*

The natural filter-feeding characteristics of daphnids mean that they are able to remove suspended solids that may not normally settle during primary clarification of wastewater. This feeding mechanism also removes some bacteria—suggesting that daphnids could be used both for clarification and disinfection of treated wastewater as a tertiary treatment [10]. Daphnids are sensitive to numerous wastewater characteristics, including ammonium, nitrite and heavy metals—which means that any system using these organisms must follow initial primary and/or secondary wastewater treatment.

The Daphniafilter aims to couple the filtering capabilities of daphnids with the nutrient transformation and removal capabilities of microalgal/bacterial biofilms. It is configured as a tank inoculated with local species of Cladocera (usually *Daphnia magna*) which are free to move up and down the water column. Internal weir and baffle mechanisms ensure that the daphnids remain within the reactor, whilst additional surface area is provided for the establishment of the microalgal/bacterial biofilm. Daphnids will remove fine suspended particles in the size range of 0.5 to 40 μm and pathogens such as coliforms and *E. coli* [10]—although the unit is not expected to provide the level of disinfection necessary for direct water re-use. However, reductions in turbidity resulting from removal of suspended solids will improve the efficacy of any final ultraviolet (UV) disinfection stage [11].

2.3. *Bio-Solar Purification*

The Bio-Solar Purification (BSP) unit is designed as a thin layer cascade photobioreactor capable of nutrient removal through microalgal uptake. It integrates a low tech and low-cost open cultivation system [12,13] with the benefits of attached-grown microalgal biofilms [14–16]. Whilst previous researchers have demonstrated good nutrient removals at bench and pilot scale, performance at commercial scale is not proven. Treatment efficacy and logistics of biofilm/biomass handling are under investigation within the current project.

Given the large surface area of the photobioreactor and exposure to UV in sunlight, pathogen reduction may also occur—although the use of an electrically-powered UV disinfection unit is recommended where treated wastewater is intended for re-use in crop irrigation or other purposes where good hygienic quality is essential. Country-specific site configurations are listed in Table 1, while a number of the pilot-scale and demonstration sites are illustrated in Figure 2.

Table 1. Demonstration site system configurations (UV = Ultraviolet; BSP = Bio-Solar Purification).

Country	Lumbrifilter	Daphniafilter	BSP	UV
Ireland	Yes			
Italy	Yes			Yes
France	Yes	Yes		
Scotland	Yes	Yes		
Turkey	Yes	Yes		Yes
Romania	Yes	Yes		
Ecuador	Yes	Yes		
Peru	Yes	Yes	Yes	Yes
Tanzania	Yes	Yes		Yes
India	Yes	Yes	Yes	Yes

Figure 2. Images illustrating the variety of locations and configurations under examination by the INNOQUA project partners. (**a**) Ireland pilot site: located alongside a conventional wastewater treatment facility in a rural location; (**b**) France: located alongside an office building in an urban location; (**c**) India: located alongside an urban community; (**d**) Ecuador: located within a small office and residential compound.

To understand system performance, data from the demonstration sites are being collected at fortnightly intervals and reported on a standard cross-site template (Table 2). The parameters tested for are reflective of wastewater discharge requirements across the various demonstration sites. In most cases it was only required (by regulation) to test for organic carbon, suspended solids, nitrogen and phosphorus. Other parameters are monitored for operational purposes.

Daily flow into each system is monitored, and the majority of project partners are submitting their samples to commercial accredited laboratories for analysis, whilst the remainder utilise their own in-house laboratory facilities and apply their own quality controls. Standard analytical methods are used, as set out in [17]:

- Chemical oxygen demand (COD) and total suspended solids (TSS) are tested in accordance with methods 5220 and 2540 respectively;
- Five-day carbonaceous biochemical oxygen demand (cBOD5) is measured in accordance with method 5210 using a nitrification inhibitor;
- Total nitrogen (TN), total phosphorus (TP) and total ammonium-nitrogen (NH_4-N + NH_3-N) are measured in accordance with methods 4500-N, 5400-P and 4500-NH_3 respectively.

All instruments and equipment used for analysis are calibrated in accordance with standards and manufacturers' instructions.

Although the project is exploring the potential for the INNOQUA solutions to achieve national discharge standards, it is also exploring the potential for treated wastewater to be re-used—particularly for irrigation purposes. In such cases the decentralised approach is delivering local sanitation and local irrigation water with minimum associated infrastructure (Table 3).

Table 2. Parameters for which data are currently being collected across all demonstration sites. In all cases data on influent and effluent from each system component are collected. TSS = Total Suspended Solids; BOD = Biochemical Oxygen Demand; COD = Chemical Oxygen Demand; N = Nitrogen.

Parameter	Lumbrifilter	Daphnia Filter	BSP	UV
TSS	Yes	Yes	Yes	
BOD	Yes	Yes	Yes	
COD	Yes	Yes	Yes	
COD (filtered)	Yes	Yes	Yes	
N-total	Yes	Yes	Yes	
NH_4-N	Yes	Yes	Yes	
NO_3-N	Yes	Yes	Yes	
NO_2-N	Yes	Yes	Yes	
Total Organic N	Yes	Yes	Yes	
Total phosphorus	Yes	Yes	Yes	
PO_4^{3-}	Yes	Yes	Yes	
pH	Yes	Yes	Yes	
Conductivity	Yes	Yes	Yes	
Dissolved Oxygen	Yes	Yes	Yes	
Turbidity	Yes	Yes	Yes	Yes
E. coli	Yes	Yes		Yes
Faecal coliforms				Yes

Table 3. Demonstration sites where treated wastewater will be re-used, and the expected use.

Country	Source of Wastewater	Expected Reuse
Ireland	Dairy and beef farm	Agricultural land or yard cleaning
France	Offices	Irrigation of ornamental plants
Turkey	Domestic dwellings and offices	Irrigation of ornamental plants
Ecuador	Domestic apartment complex	Irrigation of ornamental plants
Peru	Educational institution	Irrigation of ornamental plants
Tanzania	Domestic dwellings and training centre	Irrigation of (edible) banana crops
India	Domestic dwellings	Irrigation of crops

3. System Performance

To date, the technologies have been trialled under controlled conditions at pilot sites in Ireland and Spain. Detailed data have also been captured from replicated bench-scale experiments, which have examined specific issues such as loading rates, reactor bed depths, reactor bed materials and photobioreactor design. Data from bench-scale Lumbrifilters are presented in Table 4. Primary settled municipal wastewater was used as the influent to these systems and high rates of nitrification were observed throughout the experiments, as well as good suspended solids and organic carbon removal.

Table 4. Average removal rates of reactors with different active bed depths during steady-state operation: Bench-scale data from the National University of Ireland Galway. Each of the averages below are based on three replicates of each system. Hydraulic loading rates averaged 478 L/m^2·day and substrate loading rates averaged 293 g COD/m^2·day and 25 g NH_4-N/m^2·day (except between Days 92 and 176 where substrate loadings averaged 170 g COD/m^2·day and 16 g NH_4-N/m^2·day).

Depth of active bed layer (mm)	n	COD (%)	TSS (%)	TN (%)	NH_4-N (%)	TP (%)
700 *	25	84.0 ± 10.7	65.5 ± 40.7	64.3 ± 11.1	93 ± 8.8	68.4 ± 27.3
1000 *	25	85.5 ± 5.9	75.1 ± 18.3	63.9 ± 8.3	96.7 ± 5.7	67.1 ± 16.1
1000 **	40	71.9 ± 3.5	82.8 ± 4.2	43.1 ± 2.1	98.4 ± 0.9	98.4 ± 0.9
1300 *	25	82.2 ± 7.3	83.9 ± 10.0	65.9 ± 10.2	91 ± 8.0	73.0 ± 12.7

* Samples collected between Day 36 and Day 91. ** Samples collected between Day 92 and Day 176.

Results from the integrated 10PE (Population Equivalent) Lumbrifilter at NUI Galway's Water Research Facility are given in Table 5. The system receives settled municipal wastewater as influent at a rate of approximately 1500 L per day. The results presented are from samples taken in the period July to October 2019.

Table 5. Influent, effluent and removal efficiencies at a flow rate of 1408 ± 66 L per day: Pilot-scale lumbrifilter data from the National University of Ireland Galway (samples taken over a 90 day period).

	COD (mg/L)	TSS (mg/L)	NH_4-N (mg/L)
Lumbrifilter Influent	605 ± 285.9	69.4 ± 28.9	29.7 ± 5.4
Lumbrifilter Effluent	147.1 ± 113.2	25.6 ± 30.5	7.9 ± 8.2
% removal	70.4 ± 20.7	64.7 ± 27.7	76.1 ± 26.7

The results demonstrate that once steady-state operation is achieved, the Lumbrifilter delivers consistently high nitrification. With a fully integrated system where the Lumbrifilter effluent is fed-forward to a Daphniafilter and thence to UV or BSP, significant overall removal is anticipated. This potential is illustrated by the data in Table 6, which correspond to a combined Lumbri- and Daphniafiltration system, with measurements made after 1 and 8 days of operation at the nominal flow (1500 L per day).

Table 6. Pilot-scale data from a combined Lumbrifilter and Daphniafilter system at the University of Girona. Note that the effluent from the Lumbrifilter is the influent to the Daphniafilter.

	COD (mg/L)	TSS (mg/L)	NH_4-N (mg/L)
Lumbrifilter influent	430.3 ± 118.6	162.0 ± 68.3	33.7 ± 7.1
Lumbrifilter effluent	78.6 ± 28.5	38.8 ± 16.2	0.6 ± 0.7
Daphniafilter effluent	50.2 ± 19.1	11.6 ± 2.6	0.3 ± 0.2
% overall removal	87.7 ± 4.8	91.8 ± 3.5	94.8 ± 6.4

Operational Aspects

In addition to monitoring treatment performance, the project is developing an operating manual for this system–and logging operational experience to inform this. Particular issues have arisen with respect to sourcing local earthworms and daphnids for use in the system, since (in many cases) there are no local markets for these organisms—meaning that they have to be collected and bred from wild populations. *Daphnia* spp. are challenging to work with, and may require exposure to site-specific wastewaters for several generations before they become fully tolerant to the conditions.

All demonstration sites are operating with real wastewater under real environmental conditions to provide a good understanding of system performance with different types of wastewater, under different flow regimes and at different ambient temperatures. The system is sized to treat from 0.5 to 3 m^3 of wastewater per day and is intended to be applied to biodegradable wastewaters (from domestic/municipal/agricultural sources) rather than more recalcitrant industrial wastewaters. Observations from the project team include:

- Occasional raking of the top surface of the Lumbrifilter has been required once or twice a month during normal operating conditions.
- Occasional top-up of woodchip has been required in the Lumbrifilter—perhaps 100 mm over 4–6 months. No further maintenance has been required.
- The Lumbrifilter is very robust and recovers quickly even when flows have stopped for several weeks—providing the woodchip remains damp and does not freeze (or exceed ~35°C within the reactor). Dosing with water will keep it cool.
- In long periods where wastewater volumes are low the Lumbrifilter dosing system can be adjusted to maintain a good worm population.
- Rates of biomass accumulation at the bottom of the Daphniafilter indicate that annual de-sludging may be necessary. This can be achieved by simple siphoning or pumping, without disturbing normal filter operations.
- Daphnids consume microalgae within the attached growth, so biofilm accumulation is not expected to become problematic (although this remains under observation).
- Excess biofilm in the BSP must be removed manually. Biomass production rates are under investigation to better assess possible maintenance strategies, but in principle could be applied to land as an organic manure (directly, or following initial composting/other processing—depending on local regulatory requirements).

Biofilms established in the Daphniafilter and BSP unit are expected to accumulate phosphorus and other nutrients. The extent of the biomass growth, its management and potential to remove nutrients from the effluent are all under investigation. Specific nutrient-adsorbing media have previously been trialled within lumbrifilters [5]. While such media will become saturated over time and require replacement, there may be circumstances where such phosphorus-adsorbing media are both readily available, cost-effective and necessary to deliver final effluent of the required quality.

4. Opportunities and Challenges to Market Acceptance

Centralised (sewered) wastewater management has developed in geographies with abundant water, relatively low growth in urban density and access to adequate public funding. Such approaches do not lend themselves to scenarios where the following apply [18]:

- Water scarcity
- Dispersed settlement
- Lack of planning security
- Dynamic population development
- Low availability of public funds

Where such factors apply, decentralised nature-based solutions can have an important role. Such systems are flexible, modular and cost-effective. They can also be implemented in stages and constructed close to the sources of wastewater. This allows for adaptation to better meet the rise in demand, whilst avoiding over-capacity—providing an ideal mechanism to meet the challenges of uncertain future urban growth [19].

Furthermore, whilst it may be perceived that these issues are isolated to cities in the Global South, they can also apply in the Global North. Indeed, there are significant opportunities for decentralized solutions in EU member states with large rural populations, such as Romania. Here, around half the total population lives in rural areas, but only 10% of this population is connected to centralised wastewater collection and treatment systems—the remainder use or could use decentralised approaches [20].

Taking advantage of these opportunities requires an appropriately flexible, outcome-based regulatory approach—and widespread social acceptance. Through stakeholder interviews at demonstration site open days, the project is exploring several aspects of acceptance, including:

- Capital cost
- Operational costs
- Resource management, re-use and sustainability
- Maintenance requirements
- Visual and odour impacts
- Simplicity of installation
- Robustness

Cost and comparison with other similar systems are expected to form significant discussion points during open days. Life Cycle Costing will be applied to the system, and (where possible) like-for-like comparisons made with existing commercial technologies. Different business models for system distribution, installation and operation are also under consideration—ranging from open-source design specifications to full Design, Build, Own & Operate (DBOO).

In all cases the demonstration sites utilise tanks that have been manufactured and shipped from Europe, with ancillary fittings sourced locally. Recognising that this approach is unlikely to be cost-effective in all geographies, the project partners are currently considering options for 'showcase' sites, in which all components will be sourced locally. The ambition is that these facilities will show how the solutions can integrate into local supply chains, as well as providing opportunities for robust comparison with existing decentralised solutions.

The project team welcomes opportunities to collaborate with other research groups active in this field, and is aware that lumbri / vermi-filtration has previously been demonstrated in countries as diverse as Burkina Faso [21]; India [6]; Jordan [22]; China [23]; and Zimbabwe [24].

5. Conclusions

Through experimental and operational-scale site data we aim to show that nature-based solutions can provide low-cost sustainable wastewater treatment within both rural and urban areas across the globe—contributing to society's ability to meet the pressing challenges of sanitation and water re-use. The project team's activities at World Water Week highlighted the appetite for such systems, but also raised specific topics requiring further attention. These included:

(1) Potential for nutrient removal across the INNOQUA system
(2) Operational and maintenance requirements/costs
(3) Potential for interaction with other research groups active in the area—particularly those working with vermifiltration
(4) Potential for social acceptance to act as a barrier to market
(5) As outlined above, these aspects are all under investigation throughout the final year of the project—and detailed data will be published in line with published deliverables.

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