Performance assessment and holistic technology evaluation

Deliverable 5.5

Draft version (Confidential)

WP5 On site piloting and performance evaluation (T5.4)
Lead beneficiary: HBO

Authors: Lena Breitenmoser (FHNW), Christian Kazner (HBO), Paul Campling (VITO)
Contributors: Sofie Van Ermen (VITO), Luca Ofiera (HBO), Karina Rohrer (FHNW), Eldon Raj (IHE Delft Institute of Water Education), Alfieri Pollice (CNR-ISRA), Aditya Sharma (Indian Institute of Technology – Kanpur), Auchitya Verma (Indian Institute of Technology – Kanpur)

Approved by WP Manager:	Prof. Christian Kazner
Date of approval	31/01/2024
Approved by Project Coordinator	Dr. Paul Campling
Date of approval	31/01/2024
Due date of deliverable	31/01/2024
Actual submission date	31/01/2024

Project number (EU)	821051 (H2020-SC5-2018)
Project number (India)	BT/IN/EU-WR/39/AJ/2018
Project coordinator	Paul Campling, VITO
Scientific coordinator	Anshuman, TERI
Project web site	https://www.pavitra-ganga.eu/en

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

Dissemination level		
PU	Public	X
CO	Confidential, restricted under conditions set out in Model Grant Agreement	
CI	Classified information as referred to in Commission Decision 2001/844/EC)	
R	Document, report	X
DEM	Demonstrator, pilot, prototype	
DEC	Web sites, patent fillings, videos, etc.	
OTHER	Software, technical diagram, etc.	
ETHICS	ETHICS	

History			
Version	Date	Reason	Reviewed by
0.1	01/12/2023	First draft	Christian Kazner
0.2	22/01/2024	Second draft	Christian Kazner
1.0	31/01/2024	Final	Christian Kazner & Paul Campling

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

SUMMARY

This document assesses and compares the Pavitra Ganga treatment trains (Andicos, SFD-MBR, PAS, Andicos + CW+, SFD-MBR + CW+) against benchmark treatment trains (ASP and MBR) using a set of evaluation criteria and impact assessment methods.

The life cycle assessment showed that all Pavitra Ganga and benchmark treatment trains, focusing on energy recovery through anaerobic digestion and water reuse in agriculture (emissions to soil), have smaller environmental impacts (60 – 80%) compared to treated effluents discharged to surface water bodies (no reuse scenario). This is because the Pavitra Ganga treatment trains only removed between 40 – 50% of the phosphorous in the wastewater, which leads to freshwater eutrophication when discharged into open water bodies. On the other hand, phosphorous is an essential macronutrient for agriculture; thus, applying effluent to soils seems beneficial. Overall, the emissions to soil and the energy requirements had environmental impacts in the water reuse and energy recovery scenario. At the same time, chemicals and land use are negligible in the model. The nutrient content in wastewater is too low to provide significant environmental benefits from replacing mineral P fertilizers. The energy recovery from sludge digestion, on the other hand, reduces the environmental impacts, especially of Andicos and PAS, which assumingly have a higher energy recovery due to co-digestion of sewage sludge with biowastes and the digestion of photoactivated sludge, respectively. The cumulative environmental impacts of the Pavitra Ganga treatment trains are similar (0.0015 – 0.0023 Pts) to the reference scenarios (0.0026 – 0.0030 Pts). The polishing effect of CW+ resulted in the lowest environmental impacts due to enhanced N removal combined with small energy requirements. Future LCA studies should reflect the environmental impacts of sludge handling and application to land and micropollutant emissions.

The quantitative microbial risk assessment showed that a 2-4 log-removal is required to reduce gastrointestinal infections in the farming community to 0 – 1 infection per year. Without disinfection, SFD-MBR, PAS and the ASP processes do not achieve these log removals, and the number of gastrointestinal infections in the farming community still ranges between 98 and 485 (compared to 2,600 infections with the existing irrigation water quality). The UF membrane filtration treatment trains (i.e. Andicos and MBR) achieve > 4 log removals. Thus, the effluent should not result in any gastrointestinal infections in the farming population, even when crops are eaten raw. Andicos and MBR will also perform better in removing helminths in the wastewater than in the ASP, PAS and SFD-MBR treatment trains.

Occupational health risks for wastewater treatment plant operators are comparable in the number of risks but differ in risk levels and hazards. Enclosed membrane systems, such as Andicos, SFD-MBR and MBR, have lower risks for physical, accident and vector-related hazards than ASP or PAS. Nature-based solutions like CW+ entail a small number of hazards, as accidents related to heat, chemicals, and electricity do not exist.

The socio-technical assessment showed that SFD-MBR is the most robust system, as it showed high reliability during operation and is flexible in its design (i.e. applicable from low- to large-scale treatment schemes). It is also simpler and easier to operate than the Andicos system, which requires highly skilled personnel to operate the anaerobic process. Although Andicos shows high potential for energy recovery from co-digestion of sewage sludge and food wastes, the business model can be hampered by practical and cultural challenges related to the substrates, i.e. spatial and temporal variations as well as impurities in the substrates. SFD-MBR was assessed to be as robust as widely applied MBR or ASP processes. For the small-scale treatment scenarios, CW+ was more robust than PAS, as PAS did not operate reliably and was prone to technical failure during the pilot phase. CW+ is a reliable and simple low-tech solution that showed increased nutrient, heavy metal and organic micropollutant removal during the pilot phase. It allows for removal of contaminants of emerging concern including PFAS below limits of detection. Its flexibility is limited, as its high land requirements hinder the diffusion in urban, densely populated areas.

Annualized TOTEX for the Pavitra Ganga are similar to the benchmark systems, i.e. 18 – 25 INR/m^3/year (ASP new and MBR) > 16 – 24 INR/m^3/year (Andicos) > 14 – 21 INR/m^3/year (SFD-MBR). If energy is recovered from the treatment trains, the TOTEX can be reduced by up to 50%.

Additional expected outcomes:
This document does not integrate the multiple criteria into an aggregated score for decision-making. This is done at FHNW in an on-going MSc thesis and a peer-reviewed article (in preparation). Another MSc thesis investigates the acidification of five undigested and digested sewage sludge types from Kanpur and Delhi. It aims to understand the P and heavy metal release from the sewage sludges and its applicability for subsequent use as struvite fertilizer (Stuttgart process). A second peer-reviewed article is in preparation, which uses these results to discuss the potential of struvite recovery from sewage sludge in India and its benefits and challenges for Indian agriculture.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

TABLE OF CONTENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

LIST OF FIGURES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

LIST OF TABLES

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

CHAPTER 1 INTRODUCTION

The final task in WP5 (On-site piloting and performance evaluation) is to carry out a performance assessment and technology evaluation. This is done by analyzing the piloting results and conducting a holistic technology evaluation using economic, environmental, and social indicators.

The selection of wastewater treatment technologies should consider different criteria, such as effluent quality, treatment costs, process complexity and reliability, and electricity and land requirements (Tare & Bose, 2009; Kumar & Goyal, 2020). Common wastewater ('sewage') treatment trains in the Ganga River Basin are primary settling followed by a secondary treatment, such as sequential batch reactors (SBR), activated sludge (ASP), upflow anaerobic sludge blanket (UASB) and polishing ponds, a series of waste stabilization ponds, or membrane bioreactors (MBRs) (CPCB, 2021; Pavitra Ganga Deliverable 2.1).

The performance assessment and technology evaluation assesses and compares the Pavitra Ganga treatment trains against benchmark treatment trains using a set of evaluation criteria. We integrate the piloting results from WP3&5 (i.e. Deliverables 3.3, 3.5, 5.1 and 5.4), the treatment train comparison and modelling results (i.e. Deliverable D7.1/7.2) and the occupational health risk assessments (i.e. Deliverable D2.4) into a holistic technology evaluation. In addition, the impact potentials of wastewater treatment and reuse on human health and the environment are assessed using life cycle analysis and quantitative microbial risk assessment. Life cycle costs were calculated in Deliverable D7.2. We then compare the annualized CAPEX and OPEX of the treatment trains.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

CHAPTER 2 EVALUATION CRITERIA AND ASSESSMENT METHODS

HOLISTIC TECHNOLOGY EVALUATION CONCEPT

This document assesses the piloted treatment trains in Kanpur and Delhi (cf. WP5) using technical, economic, environmental, and social evaluation criteria (cf. Tare & Bose, 2009; Kalbar et al., 2012) (Figure 1).

The piloted treatment trains in Pavitra Ganga are considered alternative secondary and tertiary treatment processes to established wastewater treatment trains (c.f D3.5 & D5.3). Deliverable D7.2 modelled large-scale treatment train scenarios with the piloted and benchmark technologies (> 400,000 p.e.) for Kanpur. This document uses those scenarios with UV disinfection to achieve the NGT 2019 STP effluent discharge standards (Table 1). Small-scale treatment trains (< 2,000 p.e.) are added for this assessment to consider small-scale treatment solutions, such as constructed wetland plus (CW+), structured adsorbers and photoactivated sludge (PAS).

The resource (i.e. energy, chemicals and land requirements) and emission indicators (i.e. effluent qualities and sludge quantities and qualities) are then used to assess the impact potentials of the treatment trains. Life cycle analysis and life cycle cost analysis are applied to evaluate environmental and economic impacts. Quantitative microbial risk assessment estimates the potential of reduced gastrointestinal infections (Figure 1).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

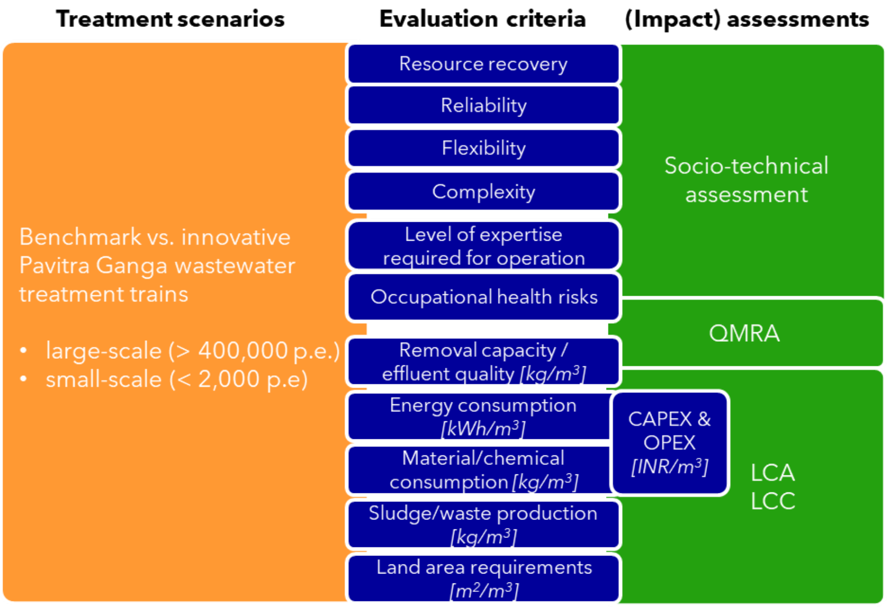

Figure 1: Holistic Technology Evaluation Concept for large- and small-scale treatment trains using multiple evaluation criteria and impact assessment methods.

TREATMENT TRAIN SCENARIOS

TREATMENT TRAINS

The treatment train scenarios are shown in Table 2. The large-scale, centralized treatment train scenarios (400,000 – 500,000 p.e.) are based on Deliverable 7.2, which compared classical upgrades (reference, R1) of the existing STP Jajmau (baseline, B) with alternative treatment trains, i.e. Andicos UF membrane and SFD-MBR as secondary treatment. The treatment trains also included sewage sludge treatment, i.e. digestion for energy recovery. If required, the treatment train scenarios are complemented with a UV disinfection process to achieve faecal coliform standards of 230 MPN/100mL (i.e., for the classical upgrade and the SFD-MBR microfiltration). An MBR treatment train (based on ultrafiltration, R2) is added to the upgraded aeration treatment trains as a second reference technology.

The small-scale treatment train scenarios (<2,000 p.e.) comprise SFD-MBR and Andicos UF membrane filtration as secondary treatment followed by CW+ as tertiary treatment (i.e. SFD-MBR + CW+ and Andicos + CW+). The PAS treatment train is also considered for decentralized, small-scale applications. Energy recovery is included in the scenarios (thermophilic digestion). Benchmark technologies are activated sludge process (reference R1) and MBR (R2).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

EFFLUENT TREATMENT AND WATER REUSE STANDARDS

The effluent qualities of the treatment train scenarios are first evaluated against the Indian effluent discharge standards (NGT, 2019). The CETP effluent discharge standard (MoEFCC, 2016) of 2 mg/L for irrigation on land is referred to for trivalent chromium.

The Indian STP effluent discharge norms for water reuse are more stringent than the EU standards for agricultural reuse (Table 1). TN and TP are not specified in the EU minimum water quality requirements for agriculture since those macronutrients can replace some mineral fertilizers.

Faecal coliform standards are 0-230 MPN/100mL, depending on the irrigated crop type. Faecal coliform standards of 1000 CFU/100mL (ca. 1000 MPN/1000mL) are allowed for drip irrigation according to EU water reuse guidelines, otherwise, standards are set lower, i.e. <10 / <100 CFU/100mL (EU, 2020). The WHO guidelines set *E. coli* standards at 1000 - 10000 CFU/100mL for unrestricted irrigation of root and leafy crops (WHO, 2006).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

Table 1: Indian effluent discharge standards (MOEFCC, 2017; NGT, 2019) and EU water reuse quality standards (EU, 2020)

Parameter	STP effluent discharge class I/ other (NGT, 2019)	Recommended norms for water reuse (CPHEEO, 2012) - agriculture			EU Water quality class A* (EC, 2020)	EU Water quality class B** (EC, 2020)
		Non-edible crops	Edible crops – raw	Edible crops - cooked		
pH	6.5-9.0					
TSS (mg/L)	30/50	30	0	30	≤10	<35
BOD (mg/L)	20/30	20	10	20	≤10	≤25
COD (mg/L)	100/150	30	Not specified	30	<125	<125
TN (mg/L)	15	10[a]	10[a]	10[a]		
TP (mg/L)	1	2	5	2		
Fecal coliforms (MPN/100mL) - desirable	230/1000	230	0	230	≤10	≤100
Helminths (egg/L)	-	< 1	< 1	< 1	≤1	≤1
Legionella ssp (CFU/L)	-	-			<1000	<1000

** all food crops, including root crops consumed raw and food crops where the edible part is in direct contact with reclaimed water- all irrigation methods;*
*** Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops to feed milk- or meat-producing animals - all irrigation methods*
[a] Norms for both Total Kjeldal Nitrogen and Nitrate are set at 10 mg/L

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

Table 2: Treatment train scenarios (all scenarios, except ASP existing, include digestion for energy recovery)

Scenario name	**Description**	**Pre-treatment**	**Primary Treatment**	**Secondary Treatment**	**Tertiary Treatment**	**Disinfection**	**Sludge treatment**
ASP existing (B)	*Present treatment Jajmau*	Fine screen/grit removal	Primary clarifier	Activated sludge w/ secondary clarifier	-	-	Sludge thickeners/ Drying beds
ASP new (R1)	*Full N-removal + disinfection*	Fine screen/grit removal	Primary clarifier	Activated sludge (fine bubble system, larger aeration tanks) w/ secondary clarifier	-	UV	Thermophilic digester/ Sludge thickeners/ Drying beds
Andicos	*Andicos alone*	Fine screen/grit removal	Primary clarifier	IPC UF membrane + ASP w/ secondary clarifier	-	-	Thermophilic digester/ Sludge thickeners/ Drying beds
Andicos + CW+	*Andicos + CW+*	Fine screen/grit removal	Primary clarifier	IPC UF membrane + ASP w/ secondary clarifier	CW+		Thermophilic digester/ Sludge thickeners/ Drying beds
SFD-MBR	*SFD-MBR + disinfection*	Fine screen/grit removal	Primary clarifier	SFD MBR	-	UV	Thermophilic digester/ Sludge thickeners/ Drying beds
SFD-MBR + CW+	*SFD-MBR + CW+*	Fine screen/grit removal	Primary clarifier	SFD MBR	CW+		Thermophilic digester/ Sludge thickeners/ Drying beds
PAS	*PAS + disinfection*	Fine screen/grit removal	Lamella settler	PAS	-	UV	Thermophilic digester/ Sludge thickeners/ Drying beds
MBR (R2)	*MBR alone*	Fine screen/grit removal	Primary clarifier	MBR	-	-	Thermophilic digester/ Sludge thickeners/ Drying beds

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

EVALUATION CRITERIA AND DATA

The treatment train scenarios are assessed comparatively applying the following criteria and indicators.

REMOVAL EFFICIENCY/ EFFLUENT QUALITY

Indicator: The removal efficiency (%) of the treatment trains of the target pollutants (BOD, COD, TSS, TN, TP, faecal coliforms) as per the Indian STP effluent treatment standards (NGT, 2019; Table 1).

Removal efficiencies of the target pollutants (BOD, COD, TSS, TN and TP) of the piloted treatment trains are discussed in Deliverables 5.3 and 5.4. Model outputs (from D7.2) or literature values are used for the benchmark treatment train scenarios.

E. coli removal (used as an indicator for faecal coliforms) was measured from June to November 2022 (published in Bablola et al., 2023; Deliverable 2.4) at 130 MLD STP Jajmau. *E. coli* removal for the alternative treatment trains is estimated from lab-scale tests (Babalola et al., 2023, D3.5), technology manufacturer specifications or literature.

Chromium removal (total chromium, CrIII and CrVI) was measured during July to September 2023 (Cedeno-Villarreal, 2023) at the 130 MLD STP Jajmau. Chromium removal for the alternative treatment trains is estimated based upon the results from technology pilots (Cedeno-Villarreal, 2023), technology manufacturer specifications or literature.

ENERGY CONSUMPTION

Indicator: The consumption of electricity (kWh/m^3) to operate the treatment train.

Energy consumption decreases exponentially when moving from small-scale to large-scale treatment plants (Gandiglio et al., 2017). The electricity consumption (kWh/m^3) is estimated per treatment train in Deliverables 3.5 and 7.2 and compared to literature values (Tare & Bose, 2009; Gandiglio et al., 2017).

CHEMICAL CONSUMPTION

Indicator: The consumption of chemicals (kg/m^3) to operate the treatment train.

Chemicals used in wastewater treatment are coagulants, flocculants, disinfection chemicals, membrane cleaning agents and antiscalants, sludge conditioners, and others. The chemical consumption for the treatment trains was assessed in Deliverable D7.2, looking at polymer equivalents needed in the primary clarifiers and for sludge conditioning. Other chemicals, such as e.g. cleaning chemicals for membranes, are not quantified for the LCA.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

SLUDGE PRODUCTION

Indicator: The quantity (kg total solids (TS)/m^3) and quality (mg of pollutants/m^3) of sewage sludge produced during the operation of the treatment train.

Sludge quantities of the treatment trains were calculated in Deliverable D7.2 and complemented with literature values for the small-scale and benchmark technologies.

Sludge quality parameters addressed in this deliverable are N and P, which could also be recovered as plant nutrients but cause a series of environmental impacts if not. In addition, total Cr levels and their effects on the environment are reported. Total N and P in sewage sludge are calculated from the removal efficiencies of the treatment trains (mass balance). Total Cr levels in sewage sludge derive from two MSc theses (Cedeno-Villarreal, 2023; Eggimann, 2024).

LAND REQUIREMENTS

Indicator: The land area (m^2/m^3) required to operate the treatment train.

Land area requirements are essential for areas with limited space, such as dense urban areas. Land area requirements per treatment train derive from literature values.

CAPEX/OPEX

Indicator: The annualized capital expenses (INR/m^3) for planning and constructing the treatment train and the annualized operational costs (INR/m^3) to operate the treatment train.

Capital expenses (CAPEX) include construction materials, technical equipment, and electrical and mechanical installations (cf. D7.2). Operational expenses (OPEX) comprise electricity costs, costs for consumables, spare parts, repairs, and labour (D7.2).

CAPEX and OPEX (electricity costs and consumables for sewage sludge dewatering) for the large-scale treatment trains are modelled in D7.2. For the small-scale treatment trains, CAPEX/OPEX are estimated from technology manufacturer specifications, key informant interviews and literature (Rohrer, 2024).

RESOURCES RECOVERY

Indicator: Potential to recover energy (gross energy recovery kWh/m3) and nutrients (potential P recovery kg P/m^3) from wastewater or sewage sludge.

The potential to recover energy from sewage sludge for the treatment trains was calculated in D7.2 and supplemented with literature values (e.g., for Andicos' co-digestion of food waste + sewage sludge).

The potential to recover nutrients from sewage sludge is based on mass balance calculations (theoretical nutrient recovery).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

ROBUSTNESS

The treatment trains' reliability, flexibility and complexity influence the wastewater treatment systems' robustness. The robustness of the treatment trains is assessed based on Pavitra Ganga's expert judgement and experiences from the Project (cf. D5.4)

Indicator: The **reliability** of the systems to achieve adequate performance for a specific period and under particular conditions (Kalbar et al., 2012)

- Variability of the treatment effectiveness under regular and extreme conditions
- Probability of technical failures
- Impact of failures upon effluent quality

Indicator: The **flexibility** to upgrade and/or increase additional hydraulic and/or organic load (Kalbar et al., 2012).

Indicator: The **complexity** of the treatment train based on

- Number of technical elements
- Complexity of technical units (low-tech vs high-tech
- Level of automation
- Availability of spare parts, chemicals and consumables in India

LEVEL OF EXPERTISE REQUIRED FOR OPERATION

Indicator: The level of expertise required to operate and maintain the treatment train (low, average, high).

Regular O&M tasks of wastewater treatment plant operators and staff include (ILO, 2012):

- Starting and stopping pumps, engines, and generators to control the flow of raw sewage through wastewater treatment plants
- Monitoring of control panels, adjusting valves and gates manually or by remote control to regulate the flow of wastewater through the wastewater treatment plant
- Inspects and observes treatment process/equipment regularly
- Collecting samples and making routine analyses of wastewater at various points in the plant process (using a dipper or bottle)
- Pumping and transferring sludge from sludge tanks to sludge disposal
- Cleaning, i.e. skimming grease, cleaning intake wells, screens and drying beds, using chemicals and detergents
- Tending pumps, conveyors, blowers, chlorinators, vacuum filters, and other equipment used to treat wastewater (e.g. lubricating, repairing parts where necessary
- Maintaining chemical feed pumps to ensure proper dosage of chemicals (checking chemical levels and refilling/replacing containers)/ manual adding of chemicals (such as ammonia or chlorine)
- Maintaining the surrounding/ wastewater treatment grounds (e.g. mowing).

The expertise required for the treatment trains is assessed based on Pavitra Ganga's expert judgement and experiences from the Project (cf. Deliverable 5.4).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

OCCUPATIONAL HEALTH RISK

Indicator: The number of low, medium, high and very high occupational health risks arising during the operation of the treatment train.

Semi-quantitative risk assessments of different wastewater treatment technologies were conducted in WP2 and presentedin Deliverable 2.4. They are based on the likelihood of an event *x* severity matrices provided by the World Health Organisation (WHO, 2015) and ILO factsheets on common occupational health hazards for wastewater treatment operators (i.e., accidents, physical, chemical, biological, ergonomic).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

CHAPTER 3 IMPACT ASSESSMENT METHODS

QUANTITATIVE MICROBIAL RISK ASSESSMENT

A quantitative microbial risk assessment (QMRA) is applied to assess gastrointestinal infections among the downstream farmers of the STP Jajmau using wastewater from irrigation canals (cf. Deliverable D2.4). The number of averted gastrointestinal infections is modelled, i.e. showing the impact of irrigation water quality improvement by implementing alternative (Pavitra Ganga) wastewater treatment trains.

The QMRA includes the four iterative steps: 1. Hazard identification, 2. Exposure assessment with and without water supply interventions, 3. Dose-response assessment, and 4. Risk characterization The QMRA method used in this report is based on established guidelines by the World Health Organization (WHO, 2016) and case studies conducted in similar low-income contexts by Fuhrimann et al., 2016a; 2016b. Table A.1 summarises the model assumptions.

HAZARD IDENTIFICATION

The hazards considered for the QMRA are five pathogenic organisms causing gastrointestinal infections in low-income settings: two types of viruses (*norovirus* and *rotavirus*), two different bacteria (*Campylobacter* spp. and *Escherichia coli*) and one intestinal protozoon (*Cryptosporidium* spp.) (WHO, 2016)

Wastewater quality in the irrigation canals was tested for *E. coli* between July and November 2022 (Deliverable 2.4; Babalola et al., 2023). The *E. coli* log removals of the Pavitra Ganga treatment trains were measured (e.g. Babalola et al., 2023) or estimated from literature (cf. Table 4 and 5)

EXPOSURE ASSESSMENT

The exposure route is through accidental ingestion of wastewater while irrigating the agricultural fields. An assumption of accidental ingestions of wastewater per day (1-10 mL) was made (Fuhrimann et al., 2016b).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

The exposure dose of the indicator bacteria *E. coli* was estimated before (S0) and after technological interventions (T1 – T4). The following exposure scenarios were modelled:

- **S0:** Accidental ingestion of untreated irrigation water (n = 235 exposure days, farmer population size 4,000; measured *E. coli* prevalence and concentrations irrigation canals, cf. D2.4)
- **T1-T4:** Accidental ingestion of treated irrigation water from treatment trains with different log removal efficiencies, which are T1 = 0.5 – 1 log removal (as for ASP or PAS treatment); T2 = 1 – 2 log removals (as for SFD MBR filtration); T3= 2-4 log removals (as for treatment trains with UV disinfection) and T4 = 4 - 7 log removals (as for Andicos UF membrane or MBR). The number of exposure days, i.e. irrigation days, is n=235, and the downstream farmer population size is 4,000 (see Deliverable D2.4); *E. coli* prevalence and concentrations measured or estimated in effluents, Table 4).

Dose-response modelling

Project evaluation and review technique (PERT) distributions are fitted to a minimum, the most likely and a maximum ratio of pathogen concentration per *E. coli* (ppath) for *rotavirus*, *norovirus*, *Campylobacter* spp. and *Cryptosporidium* spp. (Table A.1)

The ingested number of pathogens (dose; d) is calculated as $d = C_{water} \times p_{path} \times V$, where Cwater is the concentration of measured or estimated *E. coli* in irrigation water, p_{path} is the pathogen-to-pathogen ratio, and V is the volume of accidental ingestion in mL (Table A.1).

Doses (d) are used as input in the dose-response relations to obtain the probability of illness $P_{ill}(d)$ (see Fuhrimann et al., 2016a;b for 'Dose-response modelling and risk characterization equations').

Monte Carlo simulations are performed for 100,000 iterations using @Risk, version 8.2 (Palisade Corporation; Newfield, NY, USA), where one iteration simulates all the n exposure events (n different doses d) and associated $P_{ill}(d)$ of one person in a year. The expected frequency of illness for a person per year (which, in this model, can be more than one) can be calculated as the sum of the n values of $P_{ill}(d)$ obtained (without considering immunity).

Risk characterization

Model outputs are given as the incidence of gastrointestinal cases per person per year and per farming population per year.

LIFE CYCLE ASSESSMENT

A life cycle assessment (LCA) was conducted with SimaPro software and the Ecoinvent v3 database to quantify the environmental impacts of the Pavitra Ganga wastewater treatment trains. Environmental impacts of existing wastewater treatment and reuse scenarios (i.e. no treatment,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

existing ASP with reuse for downstream peri-urban agriculture) are modelled to show the environmental benefits of alternative wastewater treatment and reuse trains.

LCA follows a defined framework and four phases: 1. Goal definition & scope, 2. Life cycle inventory, 3. Impact assessment, and 4. Interpretation (ISO 14041).

Goal definition & scope

For wastewater treatment processes, an LCA considers all relevant inputs from the environment (i.e. resource indicators) and outputs into the environment (i.e. environment indicators) (Figure 2).

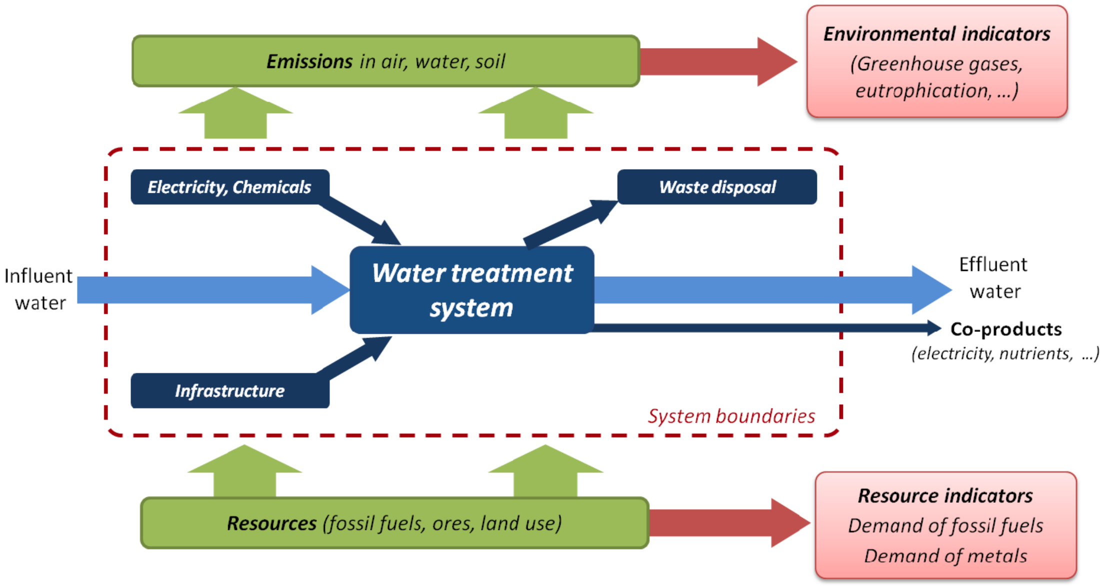

Figure 2: Typical system boundary of an LCA for a water/wastewater treatment system (Remy et al., 2013)

This LCA aims to compare alternative wastewater treatment trains for class I cities (large-scale) and decentralized applications (small-scale).

Since the Pavitra Ganga technologies and system are still under development (TRL 6-8), an early-stage LCA is conducted using pilot and literature data estimations for the LCA inventory. Early-stage or scoping LCAs can support improving the environmental performance of the piloted treatment trains by identifying and optimizing the central resource or environmental indicators (Remy et al., 2013).

Therefore, this LCA first compares the annual environmental impacts of 1 m^3 treated water by benchmark and alternative wastewater treatment trains considering the NGT 2019 effluent quality standards and CPHEEO 2012 norms (Table 1).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

Because the alternative wastewater treatment trains include sludge digestion for energy recovery and water reuse for agricultural irrigation, the avoided burden of electricity and P fertilizer use is calculated and included in the environmental impact assessments (Remy et al., 2013).

Life cycle inventory

The input flow (=resource indicators, Figure 2) considered in this document are electricity requirements (kWh/m^3), land use requirements (m^2/m^3) and chemical consumption ($kg_{chemical}/m^3$)-

For this early stage LCA, infrastructure requirements are neglected. Infrastructure has only minor impacts on the overall environmental profile due to the long lifetime of equipment (10 – 50 years). Hence, it has only minor effects on the overall environmental profiles (Remy et al., 2013; Kalbar et al., 2016)

The output flows (=environmental indicators, Figure 2) considered are the effluent water quality ($kg_{pollutant}/m^3$) and sewage sludge quality ($kg_{pollutant}/m^3$).

Impact assessment & interpretation

For the impact assessment ReCiPe 2016 v1.1, Egalitarian value choice (Mark et al., 2016) integrates the proposed set of LCA indicators for wastewater treatment impact assessment at the mid-point level (Remy et al., 2013, Table 3). Results are characterized per substance, compartment and unit and aggregated into Recipe points (Pt) per 1 m^3 wastewater. Aggregated end-point indicators are not used in this study.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

Table 3: The proposed set of LCA indicators for wastewater treatment impact assessment (Remy et al., 2013).

Impact category	Indicator	Unit	Contributing substances
Consumption of energy resources	Cumulative energy demand of fossil resources[9]	[MJ]	Hard coal, lignite, natural gas, crude oil
	Cumulative energy demand of nuclear resources[6]	[MJ]	Uranium
Climate change	Global warming potential (100a)[10]	[kg CO_2-eq]	CO_2 (fossil), N_2O, CH_4
Acidification	Terrestrial acidification potential (100 a)[7]	[kg SO_2-eq]	SO_2, NO_x, NH_3
Eutrophication	Freshwater eutrophication potential[7]	[kg P-eq]	P species in water
	Marine eutrophication potential[7]	[kg N-eq]	N species in water
Particulate matter	Particulate matter formation[7]	[kg PM_{10}-eq]	Fine dust (PM10)
Human toxicity	Human toxicity (non-cancer)[11]	[CTU_h]	Inorganic and organic toxic substances
	Human toxicity (cancer)[8]	[CTU_h]	
Ecotoxicity	Freshwater ecotoxicity[8]	[CTU_e]	Inorganic and organic toxic substances
Water scarcity	Water scarcity footprint[12]	[m^3-eq]	Water consumption

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

CHAPTER 4 SOCIO-TECHNICAL ASSESSMENT

REMOVAL EFFICIENCY/ EFFLUENT QUALITY

The effluent qualities achieved per technology are summarised in Table 4.

The average removal efficiencies (Table 5) were used to calculate effluent qualities for the life cycle inventories. The same influent characteristics as in Deliverable D7.2 were assumed. The influent characteristics are similar to the influents found in Europe. The BOD is lower, indicating that there is some degradation taking place in the sewer network. TSS and COD are elevated, indicating industrial effluents in the wastewater.

Table 4 shows the comparative assessment of calculated effluent qualities against the CPHEEO 2012 norms for irrigation of edible crops eaten raw (TSS, BOD, TP and FC) and the NGT 2019 STP discharge standards for the parameters COD, TN. The trivalent chromium is derived from the MoEFCC 2017 CETP discharge standards for irrigation (unspecified).

Table 4: Effluent qualities of treatment trains (calculated as inputs for LCA and QMRA)

	TSS (kg/m3)	BOD (kg/m3)	COD (kg/m3)	TN (kg/m3)	TP (kg/m3)	Total Cr (kg/m3)	FC (CFU/ 100ml)
Influent	1.223	0.360	1.366	0.075	0.024	0.010	1.18 * 10^8
NGT 2019 STP discharge standards- class I cities	0.030	0.020	0.100	0.015	0.001	0.002**	230
NGT 2019 STP discharge standards- others	0.050	0.030	**0.150**	**0.015**	0.001	**0.002***	1000
CPHEEO 2012 norms (edible crops - raw)	**0.030**	**0.020**	n.a.	0.010*	**0.005**	n.a.	**0**
ASP existing	0.072	0.063	0.143	0.060	0.014	0.0005	7.72 * 10^5
ASP new (R)	0.122	0.011	0.068	0.008	0.004	0.0004	100
Andicos	0.000	0.018	0.137	0.019	0.016	0.0010	0
Andicos + CW+	0.000	0.018	0.068	0.015	0.014	0.0000	0
SFD MBR	0.122	0.018	0.068	0.011	0.014	0.0004	1000
SFD MBR + CW+	0.122	0.018	0.014	0.004	0.014	0.0001	1000
PAS + UV disinfection	0.367	0.036	0.137	0.030	0.012	0.0040	1000
MBR (R)	0.000	0.018	0.068	0.011	0.014	0.0001	0

* *Norms for both Total Kjeldal Nitrogen and Nitrate are set at 10 mg/L; **total chromium levels from MOEFCC 2017 CETP discharge standards*

The existing ASP does not achieve the TSS, BOD, TN, TP and FC standards.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

Total phosphorous levels are above the standards in all treatment trains except the reference treatment train (ASP new). Additional P removal is recommended to achieve the NGT 2019 STP discharge standards of 1mg/L if water is discharged to surface water bodies. However, for water reuse in agriculture, TN and TP are macronutrients that can replace some mineral fertilizer. Thus, in the EU water reuse regulation for agriculture (2020), no concentrations are specified for TN and TP (compared to the CPHEEO norms).

Apart from TP, the treatment trains Andicos and SFD-MBR perform well. Andicos achieves all standards except TN. In combination with CW+, all standards are achieved. SFD-MBR/ SFD-MBR + CW+ does not achieve TSS and FC standards. Further disinfection of the effluent water quality is required to achieve the stringent CPHEEO 2012 norms. However, in the WHO guidelines, 1000 CFU/mL (*E. coli*) standards are set for water reuse of crops in labour-intensive agriculture. The PAS system does not achieve the standards, except for COD and total Cr, and thus does not show a reliable performance.

Total chromium standards are achieved by all treatment trains, mainly because a large part is removed already at the primary clarifier (Cedeno-Villarreal, 2023)

ENERGY CONSUMPTION

The energy requirements per treatment train are given in Table 6 (kWh/m^3) and Table 7 (qualitative). For the small-scale treatment trains, a higher electricity consumption (kWh/m^3) was assumed (Table A.2). i.e. values at the upper ranges were used, while for the large-scale treatment trains, the lower values were assumed.

The electricity requirements are very low for constructed wetlands (<0.1 kWh/m^3). The treatment trains have similar electricity requirements (0.3 – 0.55 kWh/m^3). UF membranes like Andicos and the reference treatment train MBR have slightly higher electricity requirements than SFD-MBR.

MATERIAL/CHEMICAL CONSUMPTION

Polymer equivalents are used during the primary clarifier and sludge dewatering. The amounts per m^3 of water are calculated in Deliverable D7.2 and summarised in Table 6.

SLUDGE/WASTE PRODUCTION

The quantity of sludge produced (kg total solids (TS)/m^3) and the concentrations of N, P and Cr (mg of pollutants/m^3) in the sewage sludge are summarised in Table 6, and Annex A.2 for the treatment trains.

LAND AREA REQUIREMENTS

Land area requirements for the treatment trains are estimated from literature values (Table 6 in m^2/m^3, Table 7 qualitative). Land area requirements for CW+ and PAS are very high compared to compact membrane processes (Andicos, SFD-MBR and MBR) and the conventional ASP.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

CAPEX/OPEX

The annualized TOTEX for the treatment trains were estimated based on Deliverable D7.2 and Tare & Bose (2009). Expected ranges for CAPEX & OPEX (INR/m3) are found in Table 7.

Annualized TOTEX for the large treatment trains are 18 – 25 INR/m^3/year (ASP new and MBR) > 16 – 24 INR/m^3/year (Andicos) > 14 – 21 INR/m^3/year (SFD-MBR). If energy is recovered from the treatment trains, the TOTEX can be reduced by up to 50%. For the small-scale systems, TOTEX for wetlands as the polishing step are low at 5 – 10 INR/m^3/year. TOTEX for PAS has not been calculated but is assumed to be in the range of ASP systems.

RESOURCES RECOVERY

Energy recovery (kWh/m^3) from sludge digestion is estimated from Deliverable D7.2 and literature (Table 6). Co-digestion of biowastes and sewage sludge is expected to achieve the highest energy yields; thus, the Andicos system can produce more energy than is required for its process.

Regarding nutrients, phosphorous recovery from sewage sludge is estimated using a mass balance (Table 6). This is the theoretical concentration found in sewage sludge based on the effluent qualities from the treatment trains (i.e., the phosphorous that gets removed ends up in the sludge).

An on-going MSc thesis investigates the acidification and recovery of phosphorous from digested and non-digested sewage sludges from five treatment plants in Kanpur and Delhi (Eggimann et al., 2024). The results will help to better estimate the amount of phosphorous and heavy metals that can be released and used for agriculture.

ROBUSTNESS

The robustness of treatment trains has been assessed by expert judgement and based on the piloting results (Deliverable D5.4, Table 8).

The reliability of SFD-MBR and CW+ is higher than for Andicos and PAS treatments, which showed variability in the treatment effectiveness. PAS also experienced technical issues during the piloting arising from extended rainfall and dimming of the sunlight due to weather conditions and high air pollution in Delhi.

Andicos and SFD-MBR are, like the reference treatment trains, very flexible, modular systems that can be used for small and large-scale treatment plants. CW+ and PAS are suitable for smaller-scale systems.

The simplicity and operability of Andicos are the lowest, as the anaerobic process requires experienced staff for its operation and maintenance. SFD-MBR and PAS appeared more complex to operate than conventional ASP processes. The simplest treatment process is CW+, as nature-based solutions require little automation and comprise of simple technical units.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

Table 5: Removal efficiencies of the treatment trains

Target parameters	ASP existing (B)	ASP new (R)	Andicos	Andicos + CW+	SFD MBR	SFD MBR + CW+	PAS	MBR (R)
BOD (%)	75 - 90[a,b]	75 - 99[a,c]	70 – 95[a,c]	75 - 95[a,j]	70 – 95[a,c]	75-95[a,j]	70-95[a]	95 -100[a]
COD (%)	75 - 95[a,b]	70 – 95[a,c]	70 – 90 [c,j]	75-90[c,j]	75-95[a,j]	90-95[a,j]	70-95[a]	90 - 98[a]
TSS (%)	87 - 98[a,b]	85 - 90 [a,c]	98 - 100 [a,j]		80-90[a,j]	80-90 [a,j]	50-70[a]	98 - 100[a]
TN (%)	20 - 50[c,d]	85 - 90[c]	75[j]	80[j]	85-90 [j]	95[j]	40-60[j]	90[k]
TP (%)	40 - 50[c,d]	40 - 85[b,c]	35[j]	40[j]	20-40[j]	40[j]	30-50 [j]	85[k]
E.coli (log10)	1 [e,f]	2.5 - 4[i]	4 -7 [f]	n.a	2.5 - 4[i]	1-2[a]	2.5 - 4[i]	3-7[a,l]
Total chromium (%)	95 -99[g,h]	96 -99[h]	88 -99[g]	>99[g]	96 -99[h]	>99[j]	n.a.	>90[m]

[a]Pavitra Ganga Deliverable 3.1; [b]Pavitra Ganga Deliverable 5.1; [c]Pavitra Ganga Deliverable 7.2; [d]Bajpai, 2017 (removal efficiencies of ASP systems: TP = 40 – 85%; TN= 20 – 50%); [e]Rose et al., 2004 (*E. coli* removal efficiencies in ASP: 1 – 2.5 log), [f]Babalola et al., 2022; [g]Cedeno-Villarreal, 2023 (97%); [h]Naz & Gupta, 2014 (Cr removal in ASP processes 96 – 99%); [i]Gonzalez et al., 2023 (pathogen removal with UV disinfection: 2.5 – 4.0 logs; [j]Pavitra Ganga D5.4 and data templates filled by pilot plant responsible; [k]Kitanou et al., 2021, [l] Canals et al., 2023; [m]Arevalo, 2013

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

Table 6: Technical performance evaluation of the treatment trains

Criteria	ASP existing (B)	ASP new (R)	Andicos	Andicos + CW+	SFD MBR	SFD-MBR + CW+	PAS	MBR (R)
Energy consumption (kWh/m^3)	0.3– 0.35[a]	0.3 – 0.4[b, c]	0.35 – 0.55[a,b]		0.3 – 0.5[a,b]		0.2 – 0.25[b, c]	0.4 – 0.7[a,d]
Sludge production (kg TS/m^3)	0.41[b]	0.34[b]	0.34[b]		0.34[b]		0.35-0.4[e]	0.11[f]
Polymer consumption* (kg/m^3)	Polymer equivalents: 0.005[b]	Polymer equivalents: 0.004[b]	Polymer equivalents: 0.005[b]		Polymer equivalents: 0.005[b]		Polymer equivalents: 0.005[b]	Polymer equivalents: 0.002[b]
Other operational chemical/material consumption	*n.a.*	*Cleaning chemicals*	*Cleaning chemicals*		*Cleaning chemicals*		*Cleaning chemicals*	*Cleaning chemicals*
Land area requirements (m^2/m^3)	1 – 1.4[g,h]	1 – 1.4[i]	0.45 - 0.55[g,h]	2 – 15[j,k]	0.45 - 0.55[g,h]	2 – 15[j,k]	12 - 25[l,m]	0.3 - 0.45[g,h]
Energy recovery (kWh/m^3)	n.a.	0.7[b,o]	0.7-1.9[b,p]		0.7[b]		1.1[q]	0.23[b]
Potential P recovery from sludge (kg P/m^3)	0.009	0.020	0.008		0.010		0.012	0.020

[a]Pavitra Ganga Deliverable 3.1; [b]Pavitra Ganga Deliverable 7.2; [c]US Department of Energy, 2021 (medium pressure UV = 0.1 - 0.13 kWh/m^3); [d]personal communication Xylem 19 December 2023; [e]Elawwad et al., 2017 (HRT 16 – 24 days, MLSS: 1.14 – 1.32 MLSS g/L; assuming total solids of 30%); [f]Visvanathan et al. 2000 (ca. 1/3 sludge production from activated sludge ratio). [g] Tare & Bose, 2009; [h]Kalbar et al. 2012; [i]Mazuki et al., 2020 (footprint UV: 6.36 m^2 for 5000m^3 treatment system in Malaysia, i.e., 0.001m^2/m^3); [j]Horizon2020 AquaNES Deliverable 7.2 Exploitation plans for retention soil filters (0.5 ha for 1.3 million m3 per year; 1.25 m^2/m^3); [k]Ilyas & Masih, 2017 (for vertical flow constructed wetlands 1 – 4 m^2/p.e.);[l]SSWM 2023 (high-rate algal ponds: 3 -5 m^2/m^3); [m]Delanka Pedige, 2021 (high rate algal ponds 20 – 25 m^2/m^3); [o]Enebe et al., 2023 (0.19 – 0.24 m^3 CH_4 per kg VS, assuming VS%TS is 70% and heating value of 55 MJ/kg CH_4); [p]Mata-Alvarez et al., 2014 (co-digestion of sewage sludge with food wastes in full-scale plants: 0.33 – 0.60 m^3 CH_4 per kg VS; 80:20 mixing ratio, assuming VS%TS is 75% and heating value of 55 MJ/kg CH_4); [q]Cheenakula et al., 2022 (0.3 – 0.35 m3 CH_4 per kg VS, assuming VS%TS is 70% and heating value of 55 MJ/kg CH4)

*Polymers are used to i) increase the settling velocity in clarifiers, ii) increase flocs size for mechanical separation or iii) for sludge dewatering processes to help create larger solids allowing for a better solid-liquid separation. One common polymer used in wastewater treatment is polyacrylamide.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

Table 7: Annualized CAPEX and OPEX of the treatment trains (Kumar & Goyal, 2020; Tare & Bose, 2009; Deliverable D7.2; Rohrer, 2024)

	ASP existing (B)	ASP new (R)	Andicos	SFD-MBR	CW+	PAS	MBR (R)	Waste stabilization pond
Energy requirement	High	Medium 0.189- 0.225 kWh/m3	Medium	Medium	Low	Medium	Medium to high	Very low
Annualized O&M costs	High *n.a.*	High** 8 - 10 INR/m³/year	Medium to high** 7 - 9 INR/m³/year	High** 8 - 10 INR/m³/year	Low 0.5 - 2 INR/year/m³	Medium** *n.a.*	High** 8 - 10 INR/m³/year	Low 0.5 - 2 INR/year/m³
Annualized capital cost*	Medium n.a.	High 10 - 15 INR/m³/year [b]	High 9 - 15 INR/m³/year [b]	Medium to high 6 - 11 INR/m³/year [b]	Medium 5 - 8 INR/m³/year	Medium *n.a.*	High 10 - 15 INR/m/year [3 a]	Very low 0.5 - 1 INR/m³/year [a]
Land requirements	Medium	Medium	Medium	Low	High	High	Very low	high

*Annualized CAPEX is calculated for a lifespan of 15 years; ** Annualized OPEX is calculated without cost savings from energy recovery (see Deliverable 7.2 for estimated cost savings)

[a]Activated sludge process- secondary treatment: CAPEX approximately 60% of the cost is for civil works and 40% for electrical and mechanical (E&M) work. MBR as secondary treatment; CAPEX is approximately 20% civil works and 80% E&M work. Waste stabilization ponds as tertiary treatment are 90% for civil works and 10% for E&M work.

[b]Andicos: CAPEX is 30% for civil works and 70% for E&M costs; SFD-MBR is 20% for civil works and 80% for E&M work.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

Table 8: Robustness of the treatment trains

	ASP existing (B)	ASP new (R)	Andicos	SFD-MBR	CW+	PAS	MBR (R)
Reliability (variability of treatment effectiveness, probability of technical failures)	High	Very high	Average	High	Very high	Low	High
Flexibility of design (upgradability)	Very high	Very high	High	High	Average	Average	High
Simplicity and operability (number of technical elements, simplicity of technical units, level of automation)	Average	High	Low	Average	Very high	Average	Average
Level of expertise required	Average	low	High	Average	Very Low	Average	Average

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

Level of expertise required for operation

The level of expertise required is directly linked to the indicator of simplicity and operability (Table 8). The more technical elements and the higher the level of automation, the higher the level of expertise required. ASP and CW+, thus, will require very low to low expertise, while membrane processes like MBR and SFD-MBR require average skills. High skills are needed for the Andicos system as an anaerobic process.

Occupational health risk

The total number of health risks is lower for treatment trains with fewer unit processes, i.e. the UF membrane systems MBR and Andicos (n = 64), which do not need an additional disinfection step (Figure 3, see Deliverable D2.4 for the unit process risk assessments).

The treatment trains' total risks and risk levels seem very similar (n= 77 – 82). The risk assessment per unit process shows fewer risks detected for enclosed systems such as the membrane technologies Andicos, SFD-MBR and MBR as there are, e.g. no risks for physical hazards such as UV radiation or adverse weather and fewer accident hazards. The high risks for vector-related diseases (mosquito breeding and animal bites) are lower for membrane systems than for the 'open' activated sludge systems. Nature-based systems, such as CW+, have the lowest health risks, as they are least prone to accident hazards, such as burns related to heat and chemicals or electric shocks.

The high risks in the treatment trains relate to sludge management, where contact with biological and chemical hazards is highly likely and needs safety measures when handling sewage sludge.

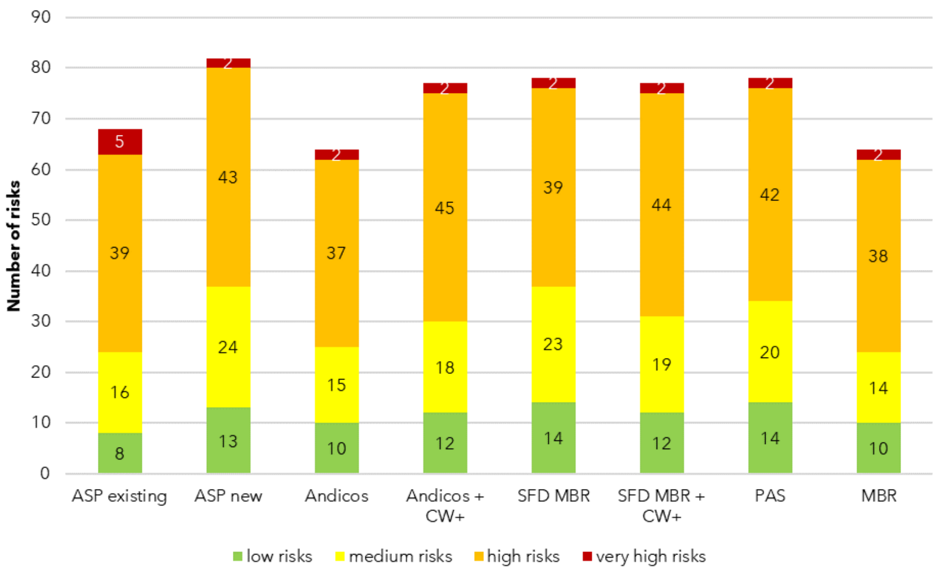

Figure 3: Number of occupational health risks related to the treatment trains

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

CHAPTER 5 QUANTITATIVE MICROBIAL RISK ASSESSMENT

NUMBER OF GASTROINTESTINAL INFECTIONS FROM UNTREATED WASTEWATER

The incidence of gastrointestinal infections per person per year, i.e. the number of gastrointestinal infections per year for a farmer using the irrigation canal water with an *E. coli* concentration between 10^5 – 10^6 CFU/100 mL, is 0.652. Over the farmer population, more than 2,600 gastrointestinal infections per year are calculated (Figure 4).

The *E. coli* (or Fecal coliform) standard is 0-230 CFU/100mL, which would result in no gastro-intestinal infections in the whole farming population. The WHO standard of 10^3 CFU/100mL results in 1 infection in the farming population (i.e., 2.5 * 10^{-4} infections per individual farmer).

REDUCED HEALTH BURDEN FROM TREATED WASTEWATER

A minimum of 4 log reductions is required to achieve the permissible *E. coli* levels of 230 CFU/100mL (non-edible crops and crops eaten cooked) and thus reduce the number of gastrointestinal infections to the WHO level of 1 infection within the downstream farming population (Figure 4).

For ASP, PAS and SFD-MBR microfiltration treatment trains, a subsequent UV disinfection or CW+ (for small-scale treatment) is required to achieve 4 log removals. Without disinfection, the yearly gastrointestinal infections in the farming community still range between 98 and 485 (80 – 95% reduction of infections in the population).

The UF membrane filtration treatment trains (i.e. Andicos and MBR) achieve > 4 log removals. Thus, the effluent should not result in any gastrointestinal infections in the farming population, even when crops are eaten raw.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

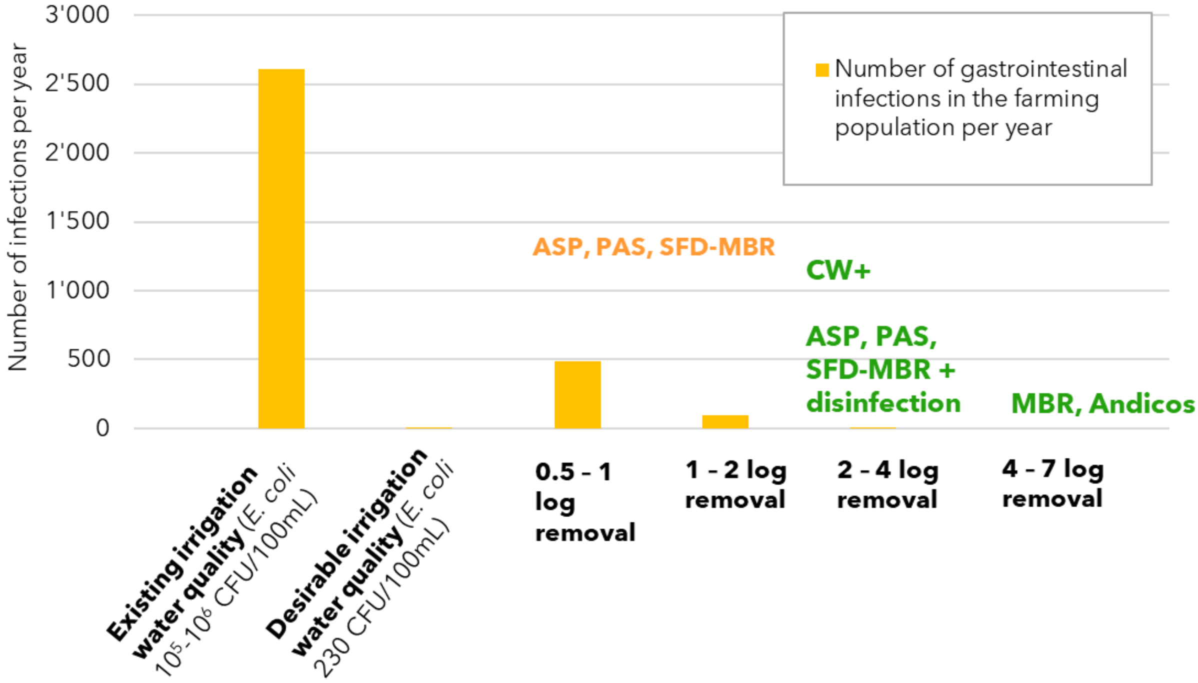

Figure 4: Number of gastrointestinal infections in the downstream farming population (n=4,000) considering different E. coli removal efficiencies of the treatment trains

Helminths were not measured in the irrigation schemes but typically pose health issues in wastewater-irrigated areas. There is a high prevalence of Ascariasis (roundworm infection) in developing countries (Jimenez et al., 2007). Wastewater contains between 40 – 3,000 eggs/L and should be reduced to < 1 egg/L to eliminate any health risks for the farmers (cf. Table 1). Removal processes used for solid particles are effective for helminth removal (Holland et al., 2022). Thus, the UF membrane processes MBR and Andicos will likely perform best to remove any helminths present in the wastewater.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

CHAPTER 6 LIFE CYCLE ANALYSIS

EMISSIONS TO WATER – NO WATER REUSE

Effluent quality has environmental impacts as it can contaminate surface waters, promote eutrophication, degrade soil quality and aggravate water scarcity (Delanka-Pedige et al., 2021) (Figure 5). However, water consumption is shown to positively impact the LCA model since properly treated wastewater can be used as an alternative to freshwater, thus alleviating water stress.

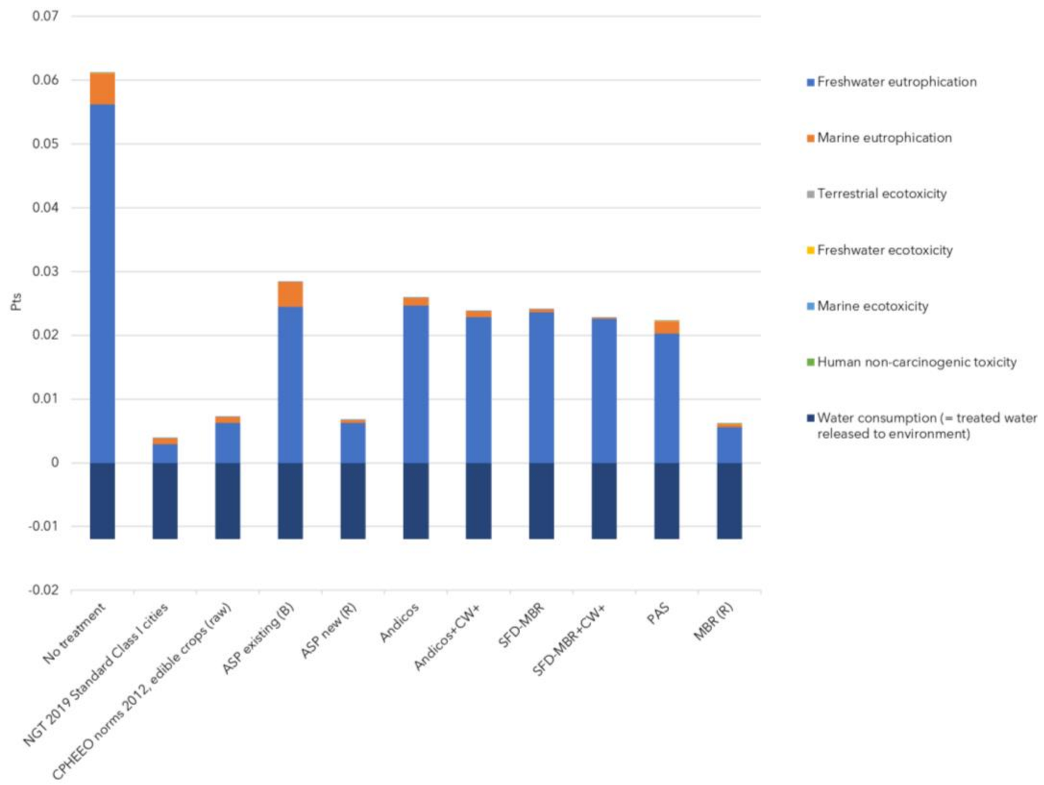

Figure 5: Environmental impacts of emissions to water 1 m³ of wastewater (in Pts). Water consumption is negative (a benefit) as wastewater treatment generates treated water that could be used as an alternative to freshwater.

Among the pollutants, the high P concentrations are problematic in the model (Table A.3 for the characterization of midpoint indicators), as they lead to freshwater eutrophication. The model inputs assumed that the reference technologies can reduce P concentrations up to 85%, thus resulting in a substantial reduction of freshwater eutrophication (90%). For the Pavitra Ganga treatment trains, the freshwater eutrophication potential is reduced by 56-64%. No apparent

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

differences were detected between SFD-MBR, Andicos and the PAS treatment trains. Additional P removal should be applied, e.g. by precipitation. This, however, will imply an increase in the environmental impacts due to material/chemical use in the process.

EMISSIONS TO SOIL – WATER REUSE

When treated water is reused for agriculture, emissions to soil can be assessed. N, P and trivalent chromium concentrations were modelled for their impacts on soil (Figure 6). Nutrient contents in wastewater (such as P) can reduce the need for mineral P fertilizer and thus be counted as an environmental benefit (avoided burden). This early-stage LCA models only the effects of P concentrations in the irrigation effluent achieved by the treatment trains. This LCA model does not consider P from sewage sludge application to soil.

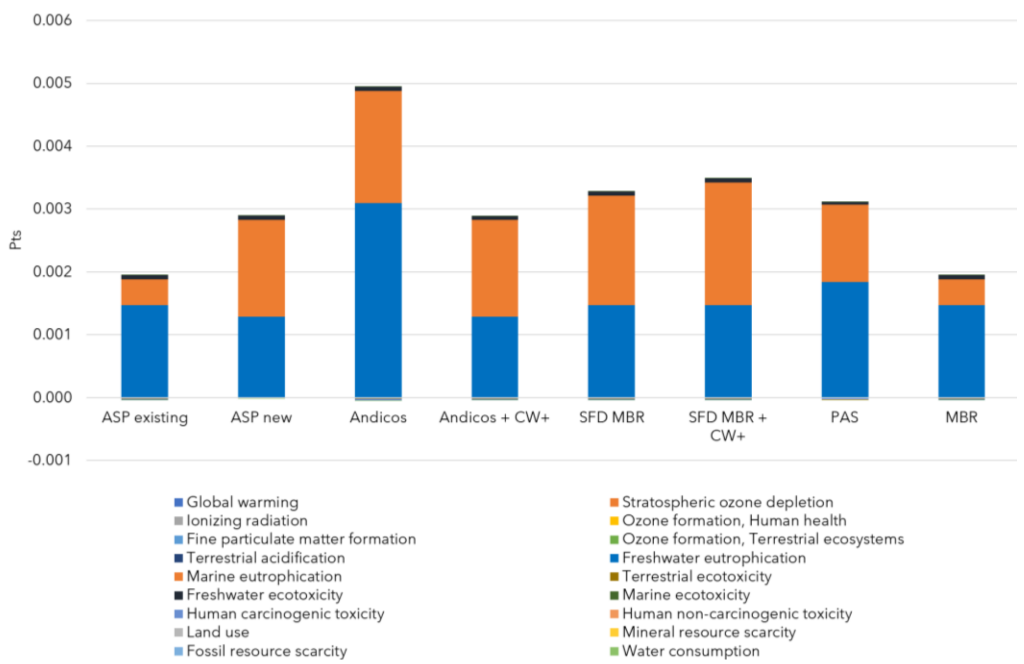

Figure 6: Environmental impacts due emissions to soil per 1 m^3 of wastewater (in Pts)

The TN concentrations lead to marine eutrophication, while TP to freshwater eutrophication if leached to surface water bodies. Compared to TN and TP, trivalent chromium has minimal environmental impacts in the model (1-4% of the total environmental impacts).

The avoided burden of reduced application of synthetic mineral fertilizers was integrated and could further reduce the total environmental impacts by 1-2%. Thus, the phosphorous content in wastewater is insufficient to provide significant environmental benefits to the water reuse scenario, as Maeseele & Roux (2021) also found.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

Yet, the LCA model suggests that emitting treated water, with nutrients such as P and N, to the soil rather than to surface water bodies can significantly reduce environmental impacts by 60 -85% (compare Figure 5).

Andicos has the highest environmental impacts, as it showed the highest TN and TP concentrations in the effluent (Table 4).

ELECTRICITY CONSUMPTION – ENERGY RECOVERY

High energy consumption contributes to the depletion of limited fossil-fuel reserves and increases greenhouse gas (GHG) emissions during energy generation (Delanka-Pedige et al., 2021).

One kWh of electricity of the Northern Indian grid has an environmental impact of almost 0.003 Pts, mainly due to human carcinogenic toxicity, fossil resource scarcity and global warming potential (Figure 7). This is primarily due to the mix of energy resources in the Northern Indian grid, which consists to > 60% of coal, which leads to harmful air pollution and greenhouse gases when fired. Electricity from the Northern grid shows a global warming potential of ca (1.1 kg CO_2-eq/kWh), similar to the Southern grid (1.2 kg CO_2-eq/kWh). The Eastern and Western grid uses more coal (1.6 kg and 1.4 kg CO_2-eq/kWh, respectively), while the North-Eastern grid involves more hydropower (0.4 kg CO_2-eq/kWh) (Hossain, 2016).

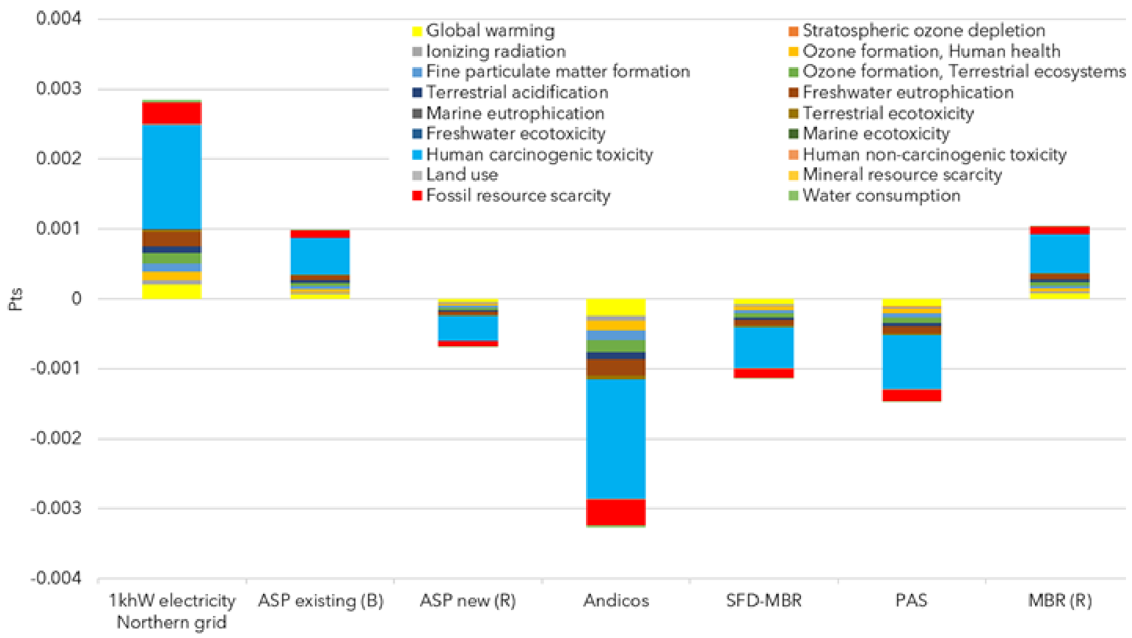

Figure 7: Environmental impacts of electricity requirements for 1 kWh of the Northern Indian grid and for 1 m³ of wastewater (in Pts)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

The net electricity use was modelled for the treatment trains. The baseline scenario has no sludge digestion and thus energy production. For the MBR, the high electricity demands (Table 6) cannot be compensated by energy recovery from sludge, as it produces less sludge than the ASP reference process. Pavitra Ganga treatment trains result in positive environmental impacts since they are net electricity producers through sludge digestion. Andicos has the highest impact, as the energy recovery is higher due to the co-digestion of sewage sludge and biowaste/food waste. Co-digestion is beneficial but can come with practical challenges with the substrate value chain, i.e. spatial and temporal variations and impurities in the substrates (Breitenmoser et al., 2019).

OTHER REQUIREMENTS

The environmental impacts of land use and chemicals have been modelled (Figure 8). Compared to the electricity requirements, these are negligible.

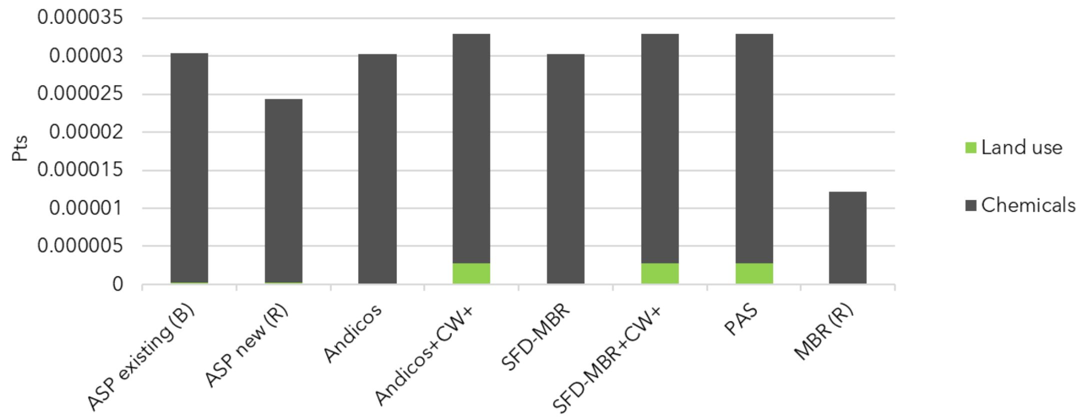

Figure 8: Environmental impacts of chemicals and land used of 1 m^3 of wastewater (in Pts)

The constructed wetland treatment trains have slightly higher impacts, as their land use (m^2/m^3) is higher than for the other treatment trains. Environmental impacts due to chemical requirements are almost the same for all treatment trains, as only polymer equivalents (i.e. polyacrylamide) were considered in the process.

CUMULATIVE IMPACTS – WATER REUSE AND ENERGY RECOVERY

The cumulative environmental impacts (negative and positive) are shown in Figure 9. The emissions to soil and the energy requirements have the highest environmental impacts, while chemicals and land use in the model are negligible. The avoided burden from discharging wastewater to soil and not surface water is not considered.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

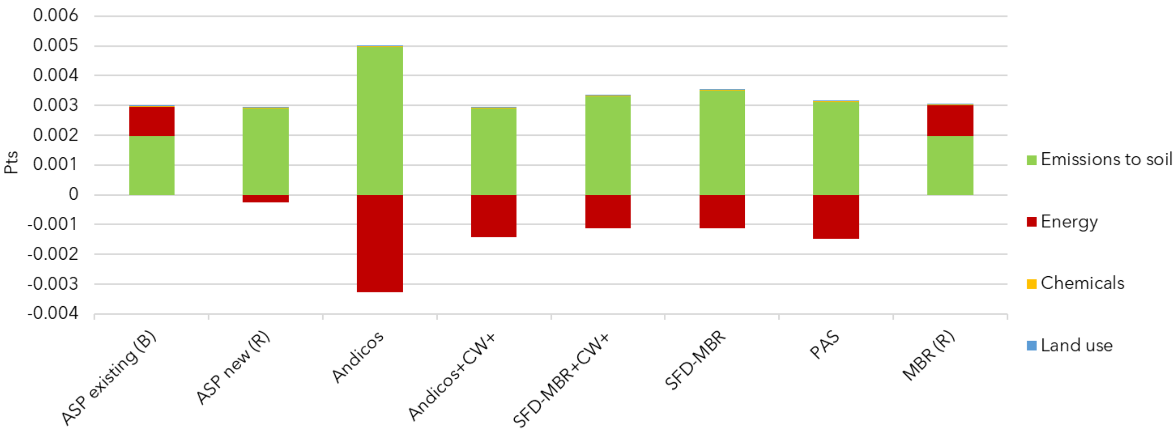

Figure 9: Cumulative environmental impacts of 1 m^3 wastewater (in Pts)

The environmental impact scores for the treatment trains are: MBR (0.0030 Pts) and ASP existing (0.0030 Pts) > ASP new (0.0026 Pts) > SFD-MBR (0.0023 Pts) > SFD-MBR + CW+ (0.0021 Pts), Andicos (0.0017 Pts) & PAS (0.0017 Pts) > Andicos + CW+ (0.0015 Pts).

The reference treatment trains (ASP new and MBR) have higher environmental impacts than the alternative Pavitra Ganga treatment trains, as the net energy requirements from sludge are smaller. Andicos and PAS have the lowest environmental impacts due to the higher energy recovery from the co-digestion of sewage sludge with biowaste and the photoactivated sludge, respectively. Andicos + CW+ has even lower environmental impacts, as more nutrients are removed and thus not leading to freshwater and marine eutrophication. SFD-MBR, with or without CW+, have similar environmental impacts. The polishing of CW+ results in slightly lower impacts due to enhanced N removal.

LIMITATIONS AND OUTLOOK

The LCA model does not consider the level of local water scarcity or the origin of the local water resources (Maeseele & Roux, 2021). Pollutants and nutrients removed in the wastewater treatment may end up in the sewage sludge and should be assessed for environmental impacts in future studies. Also, the environmental impacts (negative and positive) of micropollutant removal should be addressed for the Indian context.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

CONCLUSIONS

The life cycle assessment revealed that all Pavitra Ganga treatment trains, focusing on energy recovery through anaerobic digestion and water reuse in agriculture (emissions to soil), can reduce the total environmental impacts by 60-80%% compared to treated effluents discharged to surface water bodies. This is due to the high P contents in the effluents that lead to freshwater eutrophication in open water bodies but, on the other hand, is an essential macronutrient in agriculture. However, the phosphorous content in wastewater is insufficient to provide significant additional environmental benefits from reduced use of mineral P fertilizers. On the other hand, the energy recovery from sludge digestion reduces the environmental impacts, especially of Andicos and PAS. Overall, the cumulative environmental impacts of the Pavitra Ganga treatment trains are comparable (0.0015 – 0.0023 Pts) to the benchmark scenarios (0.0026 – 0.0030 Pts). The polishing effect of CW+ results in the lowest environmental impacts due to enhanced N removal combined with low energy requirements.

The quantitative microbial risk assessment showed that disinfection processes are required for SFD-MBR, PAS and the ASP processes to achieve a 2-4 log-removal of faecal coliforms. Without disinfection, SFD-MBR, PAS and the ASP processes do not achieve these log removals, and the number of gastrointestinal infections in the farming community still ranges between 98 and 485 (compared to 2,600 infections with the existing irrigation water quality). The effluents of the UF membrane treatment trains (i.e. Andicos and MBR) will mitigate gastrointestinal infections and remove helminths effectively.

Occupational health risks for wastewater treatment plant operators are comparable in the number of risks but differ in risk levels and hazards. Enclosed membrane systems, such as Andicos, SFD-MBR and MBR, have lower risks for physical, accident and vector-related hazards than ASP or PAS. CW+ entails fewer hazards, as accidents related to heat, chemicals and electricity do not exist.

The socio-technical assessment showed that SFD-MBR is the most robust system, as it demonstrated high reliability during operation and it is flexible in its design (i.e. applicable from low- to large-scale treatment schemes). It is also simpler and easier to operate than the Andicos system, which requires highly skilled personnel to operate the anaerobic process. Although Andicos shows high potential for energy recovery from the co-digestion of sewage sludge and biowastes, the business model can be hampered by practical and cultural challenges. Among the small-scale treatment scenarios, CW+ is more robust than PAS, as PAS was prone to technical issues during piloting. CW+ is a reliable and simple low-tech solution with increased nutrient and heavy metal removal.

Further expected outcomes:
This document provides multiple criteria to be aggregated into a score for decision-making which is done in an ongoing MSc thesis and peer-reviewed article in preparation (FHNW). Another MSc thesis and peer-reviewed article (in preparation at FHNW) investigate the acidification of five undigested and digested sewage sludge from Kanpur and Delhi to understand the P and heavy metal release from the sewage sludge and for subsequent use as struvite fertilizer (see references).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

REFERENCES

Pavitra Ganga Deliverables:

Cuadrado-Quesada G, Breitenmoser L, Hooijmans C, Anshuman, Phukan M, Dkhar N, De Schamphelaere H, Campling P (2020). Poliy brief on determinants of successful and unsuccessful urban wastewater treatment, water re-use and resource recovery models. **Deliverable 2.1**. EU Horizon 2020 Pavitra Ganga, GA No. 821051

Breitenmoser L & Furlong C,Anshuman, Campling P & Hooijmans C (2024). Technology-specifiv wastewater safety plans for the two on-site pilots. **Deliverable 2.4**. EU Horizon 2020 Pavitra Ganga, GA No. 821051

Van Ermen S, de Valk S, Kazner C (2020). Identification of the boundary conditions for technology development under Indian conditions, inluding factsheets of PAVITRA GANGA benchmark technologies and innovations. **Deliverable 3.1**. EU Horizon 2020 Pavitra Ganga, GA No. 821051

Piaggo A, de Kreuk M, Van Ermen S, Campling P (2023). Laboratory test reports and fact sheets on nutrient recovery, biogas quality and options for biogas use, as well as effluent qualities and water reuse possibilities. **Deliverable 3.3**. EU Horizon 2020 Pavitra Ganga, GA No. 821051

Ofiera L, Van Ermen S, de Valk S, Kazner C (2020). Excel Sheet with influent characteristics of the two pilot locations.**Deliverable 5.1**. EU Horizon 2020 Pavitra Ganga, GA No. 821051

Van Ermen S, Zia S, Bose P, de Valk S, Kazner C, Ofiera O, Pollice A, Raj E, Michielsen B, Garcia H, Shah S (2022). Design of piloted innovative treatment and recovery technologies. **Deliverable 5.3.** EU Horizon 2020 Pavitra Ganga, GA No. 821051

Ofiera L et al.(2024). Monitoring and operation of piloted technologies. **Deliverable 5.4.** EU Horizon 2020 Pavitra Ganga, GA No. 821051

Fenu A, De Schaempelaere H, Campling P, Van Ermen S, Bose P, Boonen I (2022). A proposed road map to exploit the wastewater treatment, water reuse and resource recovery opportunities in Kanpur (India). **Deliverable 7.1**. EU Horizon 2020 Pavitra Ganga, GA No. 821051

Boonen I (2023). Investment and financing programme to exploit the wastewater treatment, water-reuse and resource recovery opportunities for a selected urban local body in Kanpur. **Deliverable 7.2**. EU Horizon 2020 Pavitra Ganga, GA No. 821051

MSc theses and publications in prepration:

Rohrer K (under preparation). Multiple Criteria Analysis Assessment of Pilot Wastewater Technologies in the Pavitra Ganga Project in India. MSc thesis Life Sciences FHNW. To be submitted on 19 February 2024.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

Rohrer K & Breitenmoser L, Hugi C, Kazner C (under preparation). Multi-criteria analysis for wastewater reuse and recovery in India. In preparation for special Issue in *Water* on 'Resource Recovery Monitoring and Circular Economy Model in Wastewater'

Eggimann S (in preparation). Struvite recovery from sewage sludge in India. MSc thesis Life Sciences FHNW. To be submitted in June 2024.

Eggiman S, Sharma A, Breitenmoser L (in preparation). Acidification and recovery of struvite from digested and non-digested sewage sludge in India. In preparation for *Resources, Conservation and Recycling.*

Other references:

Arévalo J, Ruiz L, Parada-Albarracin J, Gonzalez-Peret D et al. (2012). Wastewater reuse after treatment by MBR. Microfiltration or ultrafiltration? Desalination. 10.1016/j.desal.2012.05.008

Babalola FM, Breitenmoser L, Furlong C, Campling P, Hooijmans CM (2023). Occupational Health Risk Assessment for Wastewater Treatment and Reuse in Kanpur, India. *International Journal of Environmental Research and Public Health*. https://doi.org/10.3390/ijerph20126072

Bajpai P (2017). Chapter 6 – External Treatment Technologies Used for Pulp and Paper Mill Effluents. Pulp and Paper Industry. https://doi.org/10.1016/B978-0-12-811099-7.00006-X

Breitenmoser, L., Gross, T., Huesch, R., Rau, J., Dhar, H., Kumar, S., Hugi, C. and Wintgens, T. (2019) Anaerobic digestion of biowastes in India: Opportunities, challenges and research needs. *J Environ Manage*. doi:10.1016/j.jenvman.2018.12.014.

Canals J, Cabrera-Codony A, Carbó O, Torán J, Martín M et al. (2023). High-rate activated sludge at very short SRT: Key factors for process stability and performance of COD fractions removal, Water Research. https://doi.org/10.1016/j.watres.2023.119610

Cedeno-Villarreal M (2023). The Fate of Chromium in Wastewater Treatment and Reuse, and the associated occupation healh risks in Kanpur, India. MSc thesis. IHE Delft, Institute for Water Education.

Cheenakula, D., Hoffstadt, K., Krafft, S. et al. Anaerobic digestion of algal–bacterial biomass of an Algal Turf Scrubber system. Biomass Conv. Bioref. 13, https://doi.org/10.1007/s13399-022-03236-z

CPHEEO, Central Public Health and Environmental Engineering Organisation, Government of India (2012) Manual on sewerage and sewage treatment. Part A Engineering, New Delhi: Ministry of Urban Development.

Delanka-Pedige H, Munasinghe-Arachchige S, Abeysiriwardana-Arachchige I, Nirmalakhandan N (2021). Evaluating wastewater treatment infrastructure systems based on UN Sustainable Development Goals and Targets. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2021.126795

Elawwad A, Karam A, Zaher K (2017). Using an Algal Photo-Bioreactor as a Polishing Step for Secondary Treated Wastewater. Pol. J. Environ. Stud. DOI: 10.15244/pjoes/68426

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

Enebe NL, Chigor CB, Obileke K, Lawal MS, Enebe MC (2023). Biogas and Syngas Production from Sewage Sludge: A Sustainable Source of Energy Generation. *Methane*. https://doi.org/10.3390/methane2020014

EU, European Union (2020). Regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020 on minimum requirements for water reuse. eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R0741&from=EN

Fuhrimann S, Pham-Duc P, Cissé G, Thuy Tram N, Thu Ha H, Trung Dung D, Ngoc P, Nguyen-Viet H, Anh Vuong T, Utzinger J, Schindler C, Winkler M. 2016a. Microbial contamination along the main open wastewater and storm water channel of Hanoi, Vietnam, and potential health risks for urban farmers, Science of The Total Environment, https://doi.org/10.1016/j.scitotenv.2016.05.080.

Fuhrimann S, Winkler M, Stalder M, Niwagaba C, Babu M, Kabatereine N, Halage A, Utzinger J, Cissé G, Nauta M. 2016b. Disease burden due to gastrointestinal pathogens in a wastewater system in Kampala, Uganda, Microbial Risk Analysis, https://doi.org/10.1016/j.mran.2016.11.003.

Gandiglio M, Lanzini A, Soto A, Leone P, Santarelli M (2017). Enhancing the Energy Efficiency of Wastewater Treatment Plants through Co-digestion and Fuel Cell Systems. Front. Environ. Sci. https://doi.org/10.3389/fenvs.2017.00070

González Y, Gómez G, Moeller-Chávez GE, Vidal G. UV Disinfection Systems for Wastewater Treatment: Emphasis on Reactivation of Microorganisms. Sustainability. 2023; 15(14):11262. https://doi.org/10.3390/su151411262

Holland C, Sepidarkish M, Deslyper G, Abdollahi A, Valizadeh S, Mollalo A, Mahjour S, Ghodsian S, Ardekani A, Behniafar H, Gasser RB, Rostami A. Global prevalence of Ascaris infection in humans (2010-2021): a systematic review and meta-analysis. Infect Dis Poverty. doi: 10.1186/s40249-022-01038-z

Hossain M (2016). Regionalized Life Cycle Inventory of Power Producing Technologies and Power Grids in India. MSc thesis. Chalmers University of Technology. Gothenburg, Sweden. Hossain_2016_Electricity_production_and_distribution_India_regionalized.docx (chalmers.se)

ILO, International Hazard Datasheets on Occupation (2012). Wastewater Treatment Plant Operator. Occupational Hazard Datasheets - Wastewater Treatment Plant Operator (ilo.org)

Ilyas, H., Masih, I. Intensification of constructed wetlands for land area reduction: a review (2017). Environ Sci Pollut Res 24, 12081–12091. https://doi.org/10.1007/s11356-017-8740-z

ISO 14040 :2006 : Environmental management. Life cycle assessment. Goal and scope definition and inventory analysis.

Jiménez B, Maya C, Galvan M (2007). Helminth ova control in wasetwater and sludge for advanced and conventional sanitation. Water Science & Technology. doi: 10.2166/wst.2007.555

Kalbar P, Karmakar S & Asolekar S (2012). Technology assessment for wastewater treatment using multiple-attibute decision-making. Technology in Society. https://doi.org/10.1016/j.techsoc.2012.10.001

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

Kalbar P, Karmakar S & Asolekar S (2016). Life cycle-based decision support tool for selection of wastewater treatment alternatives. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2016.01.036

Kitanou S., Ayyoub H., Touir J., Zdeg A., Benabdallah S., Taky M. & Elmidaoui A. 2021 A comparative examination of MBR and SBR performance for municipal wastewater treatment. Water Practice and Technology. https://doi.org/10.2166/wpt.2021.016

Kumar& Goyal (2020). Chapter Two- Water reuse in India: Current perspective and future potential. Advances in Chemical Pollution, Environmental Management and Protection, https://doi.org/10.1016/bs.apmp.2020.07.011

Maeseele C & Roux P (2021). An LCA framework to assess environmental efficiency of water reuse : Application to contrasted locations for wastewater reuse in agriculture. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2021.128151

Mark A.J. Huijbregts, Zoran J.N. Steinmann, Pieter M.F. Elshout, Gea Stam, Francesca Verones, Marisa Vieira, Michiel Zijp, Anne Hollander, Rosalie van Zelm. ReCiPe2016: a harmonized life cycle impact assessment method at midpoint and endpoint level(link is external). International Journal of LCA, DOI 10.1007/s11367-016-1246-y.

Mata-Alvarez J, Dosta J, Romero-Güiza M, Fonoll X, Peces M, Astals S (2014). A critical review on anaerobic co-digestion achievements between 2010 and 2013. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2014.04.039

Mazuki N, Teow Y, Ho K, Mohammad A (2020). Techno-economic analysis of single disinfection units and integrated disinfection systems for sewage effluent reclamation, Journal of Water Process. https://doi.org/10.1016/j.jwpe.2020.101398

MoEFCC, Ministry of Environment, Forest and Climate Change, Government of India (2016). Common effluent treatment plant discharge standards.

Naz A & Gupta SK (2014). Remediation of Low Level Hexavalent Chromium from Water by Activated Sludge Process: A Review. In Strategic Technologies of Complex Environmental Issues – A Sustainable Approach. Mishra GC (ed.) Excellent Publishing House, New Delhi.

NGT, National Green Tribunal (2019) Original Application No. 1069/2018 (M.A. No. 1792/2018, M.A. No. 1793/2018, I.A. No. 150/2019 & I.A. No.151/2019), http://www.indiaenvironmentportal.org.in/files/file/revised-standards- STPs-NGT-Order.pdf,

Remy C, Wencki K, Pieron M, Kounina A, Hugi C, Gross T (2013). Final guidelines for sustainability assessment of water technologies. Deliverable 51.2. EU FP7 DEMEAU GA No. 308339

Rose JB, Farrah S.R, Harwood V.J., Levine A.D., Lukasik J, Scott T.M. (2004). Reduction of Pathogens, Indicator Bacteria, and Alternative Indicators by Wastewater Treatment and Reclamation Processes; Final Report; Water Environment Research Foundation: Alexandria, VA, USA, 2004.

Tare & Bose (2009). Compendium on Sewage Treatment Technologies. National River Conservation Directorate. Ministry of Environment & Forests, Government of India. https://nmcg.nic.in/writereaddata/fileupload/15_Technologies%20Involved.pdf

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

US Department of Energy (2021). Energy for disinfection (https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/Tipsheet%205%20-%20UV%20Disinfection%20-%20Final.pdf)

WHO (2006). WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater (Volume IV: Excreta and greywater use in agriculture). World Health Organization (WHO), Geneva, Switzerland, ISBN: 92 4 154685 9

World Health Organization. (2015). Sanitation safety planning: manual for safe use and disposal of wastewater, greywater and excreta. World Health Organization. https://apps.who.int/iris/handle/10665/171753

World Health Organization. (2016). Quantitative Microbial Risk Assessment: Application for Water Safety Management. ISBN 978 92 4 156537 0

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

ANNEX A

Table A.1: QMRA model assumptions adapted from Fuhrimann et al., 2016b

Description	Unit	Distribution and/ or value(s)	References
(C_{water}) Concentrations in wastewater (irrigation canals)			Measured data (D5.4; D2.4) & literature values
E. coli	log_{10} (CFU/100 mL)	S0: Normal (5.4;0.89); prevalence = 1.0	
(C_{water}) Concentrations in treated wastewater			
E. coli	log_{10} (CFU/100 mL)	T1: 0.5 – 1 log removal: PERT (0.5;0.75;1) T2: 1 – 2 log removal: PERT (1;1.5;2) T3: 2 - 4 log removal: PERT (2;3;4) T4: 4-7 log removal: PERT (4;5.5;7)	
(p_{path}) Ratio between indicator and pathogenic organisms			
Campylobacter spp. to *E. coli*	CFU/CFU	PERT (0.1;0.55;1)** per 10^5 *E. coli*	WHO, 2006
Cryptosporidium spp. to *E. coli*	CFU/CFU	PERT (0.01;0.055;0.1)** per 10^5 *E. coli*	Shere et al., 2002;
Pathogenic *E. coli* O157:H7 to *E. coli*	CFU/CFU	Uniform ($7.6x10^{-4}$; $1x10^{-2}$)**	Shere et al., 2002; Soller et al., 2010; Hynds et al., 2014
Norovirus to *E. coli*	CFU/CFU	PERT (0.1;0.55;1)** per 10^5 *E. coli*	WHO, 2006
Rotavirus to *E. coli*	CFU/CFU	PERT (0.1;0.55;1)** per 10^5 *E. coli*	Fuhrimann et al., 2016d; Katukiza et al., 2013
(V) Volume drinking water consumed per exposure event (day)			
$S_{accidental\ ingestion}$	mL	PERT (1;6;10)***	Fuhrimann et al., 2016b
Dose-response models			
A. lumbricoides		Point estimate: α = 0.0104; N_{50} = 859	Mara and Sleigh, 2010
Campylobacter spp.		Point estimate: α = 0.145; N_{50} = 896	Medema et al., 1996
Cryptosporidium spp.		Point estimate: r = 0.0042	Haas et al., 1999
E. coli O157:H7		Point estimate: α = 0.49; N_{50} = 596,000	Teunis et al., 2008a
Norovirus		Point estimate: α = 0.04; β = 0.055;	Teunis et al., 2008b

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

Rotavirus		Point estimate: α = 0.253; N_{50} = 6	Teunis and Havelaar, 2000
(λ) **Illness to infection ratio**			
Campylobacter spp.		Point estimate: 0.3	Machdar et al., 2013
Cryptosporidium spp.		Point estimate: 0.79	
Pathogenic *E. coli*		Point estimate: 0.35	
Norovirus		Point estimate: eta = 0.00255; r = 0.086	Teunis et al., 2008b
Rotavirus		Point estimate: 0.5	Barker, 2014
(n) Number of exposure events per year (days)		Point estimates S0 and T1-T4: 235	D2.4
(Pop_E) Population at risk		4,000 farmers	D2.4

*Normal distribution (mean; standard deviation); **Project evaluation and review techniques (PERT) (min; most likely; max), *** full references in this model assumption table can be found in Fuhrimann et al., 2016b

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.

Table A.2: Life cycle inventory for 1 m3 of treated wastewater

	Energy	Chemicals	Sludge (emissions to soil)			Effluent (emissions to water)						Land area
Scenario Name	Energy net consumption (kWh/m3)	PE consumption (kg/m3); acrylamide	P (kg/m3)	N (kg/m3)	Cr (kg/m3)	TSS (kg/m3)	BOD (kg/m3)	COD (kg/m3)	TN (kg/m3)	TP (kg/m3)	Cr (kg/m3)	(m2/m3)
No treatment	n.a.	n.a.	n.a.	n.a.	n.a.	1.223	0.36	1.366	0.075	0.024	0.0102	n.a.
Any treatment reaching NGT 2019 STP discharge standards for	n.a.	n.a.	n.a.	n.a.	n.a.	0.03	0.02	0.1	0.015	0.001	0.002	0
Any treatment reaching NGT 2019 STP discharge standards for	n.a.	n.a.	n.a.	n.a.	n.a.	0.05	0.03	0.15	0.015	0.001	0.002	n.a.
ASP existing	0.35	0.004786648	0.0096	0.015	0.00969	0.072	0.063	0.143	0.06	0.0144	0.00051	1.4
ASP new	-0.09	0.004	0.02016	0.0675	0.009792	0.0365	0.00564	0.0252	0.0075	0.00384	0.000408	1
Andicos	-1.15	0.004975594	0.0084	0.05625	0.00918	0	0.0094	0.0504	0.01875	0.0156	0.00102	0.5
Andicos + CW+	-0.5	0.005	0.0096	0.06	0.010098	0	0.00705	0.0252	0.015	0.0144	0.000102	12
SFD MBR	-0.3	0.004818139	0.0096	0.06375	0.009792	0.0365	0.0094	0.0252	0.01125	0.0144	0.000408	0.5
SFD MBR + CW+	0.01	0.005	0.0096	0.07125	0.010098	0.00365	0.00705	0.0252	0.00375	0.0144	0.000102	12
PAS	-0.52	0.005	0.012	0.045	0.00612	0.1095	0.0094	0.1512	0.03	0.012	0.00408	15
MBR	0.539	0.002	0.0204	0.0675	0.00918	0	0.00045	0.0252	0.0075	0.0036	0.00102	0.45

Table A.3: Characterization of midpoint indicators per impact category and effluent quality of treatment trains

Impact categ	Unit	No treatmen	Standard	Standard	ASP existing	ASP new (R)	Andicos	Andicos+CW	SFD-MBR	SFD-MBR+CV	PAS	MBR (R)
Freshwater e	kg P eq	0.03653076	0.0018712	0.0023068	0.01589556	0.0040639	0.01603415	0.01483233	0.0146512	0.01533654	0.01316596	0.00365024
Marine eutro	kg N eq	0.022275	0.004455	0.004455	0.01782	0.0022275	0.00556875	0.004455	0.00334125	0.0022275	0.00891	0.0022275
Terrestrial e	kg 1,4-DCB	6.07E-18	1.19E-18	1.19E-18	3.03E-19	2.44E-19	6.07E-19	5.95E-20	2.44E-19	2.44E-19	2.43E-18	6.07E-19
Freshwater e	kg 1,4-DCB	0.02346	0.0046	0.0046	0.001173	0.000943	0.002346	0.00023	0.000943	0.000943	0.009384	0.002346
Marine ecoto	kg 1,4-DCB	5.304	1.04	1.04	0.2652	0.2132	0.5304	0.052	0.2132	0.2132	2.1216	0.5304
Human non-	kg 1,4-DCB	0.0004998	9.80E-05	9.80E-05	2.50E-05	2.01E-05	5.00E-05	4.90E-06	2.01E-05	2.01E-05	0.00019992	5.00E-05
Water consu	m3	-3.1781027	-3.1781027	-3.1781027	-3.1781027	-3.1781027	-3.1781027	-3.1781027	-3.1781027	-3.1781027	-3.1781027	-3.1781027

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821051.
This project has been co-funded by Department of Biotechnology (DBT), Government of India.