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Nature-Based Solutions and Life Cycle Analysis for Aquatic Biodiversity in Wastewater Treatment

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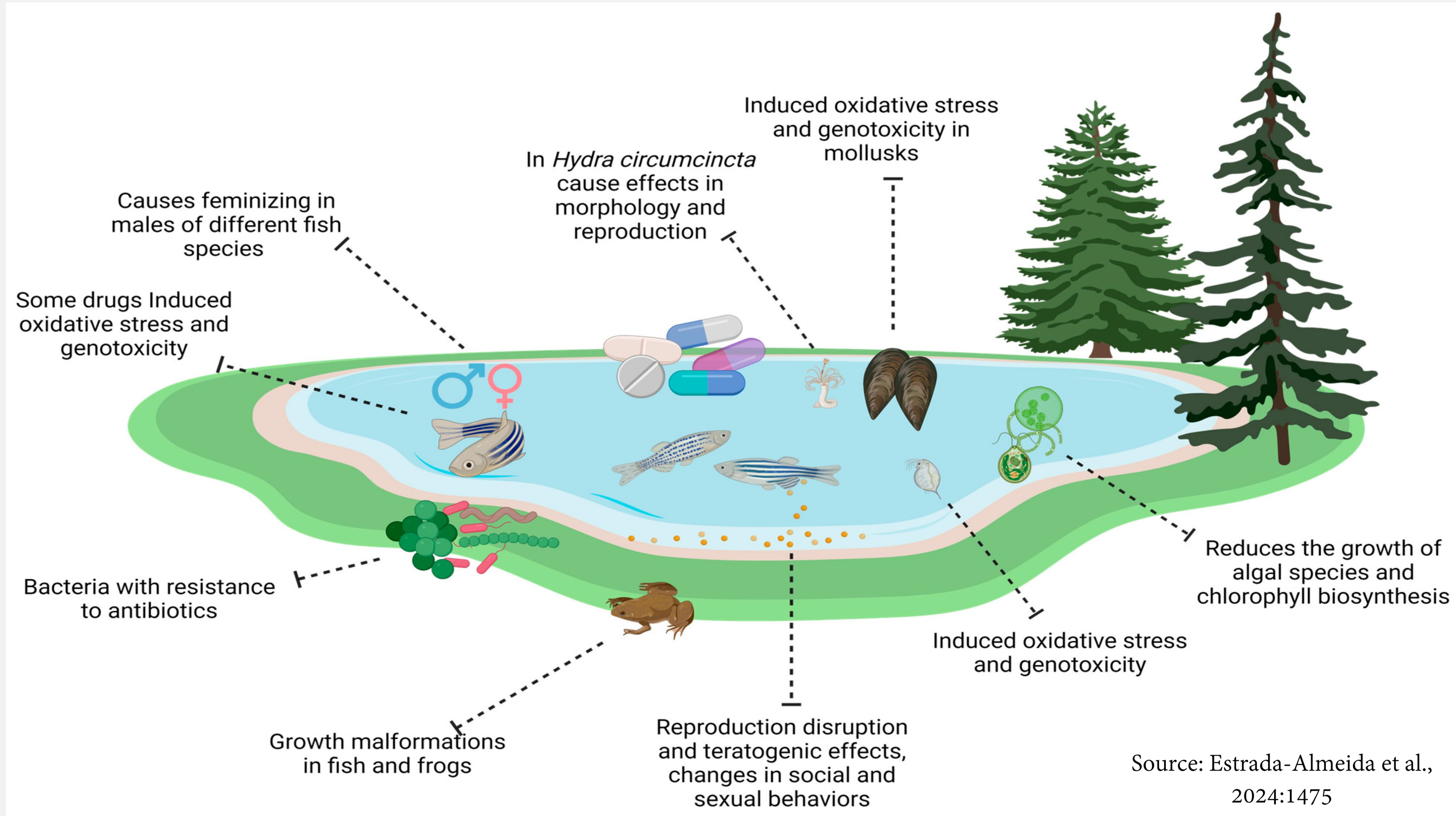
Introduction

Pollution is a key driver affecting biodiversity loss. Part of the pollution comes from essential human activities, such as health care and food production through the use of pharmaceutical products (PP). **Aquatic environments are quite vulnerable to PP pollution**, both structure and functionality. Consequently, as traditional wastewater treatment plants cannot eliminate PP completely, and PP consumption increases steadily, there are resultant health threats to humans and ecosystems. However, some treatments are expensive and energy demanding. **Nature based Solutions (NbS), harnessing natural processes and ecosystems functioning, can help addressing these challenges.**

The international research project

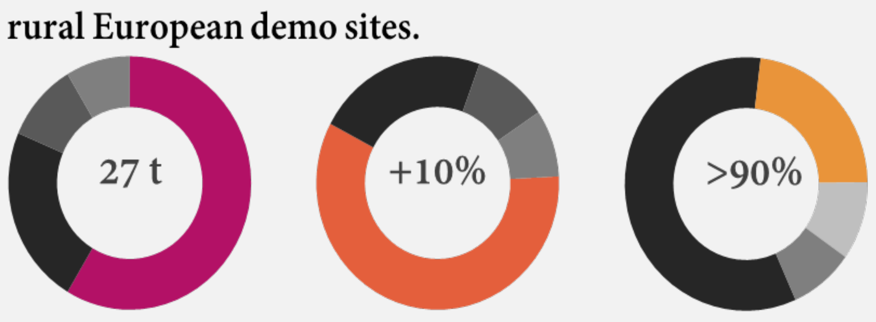
NBS4AQUAMISSION project aims to leverage nature-based systems (NbS) in a combined triad solution of **treatment wetlands** (mimicking natural ecosystems), **innovative materials** (e.g. bio- and hydrochars) and **bioaugmentation** (increasing remediation capacity of active microbes) to mitigate PP pollution impacts posed on the aquatic biodiversity and assess the NBS implementation effects over time and space.



Rising environmental levels of pharmaceuticals pose a global threat by endangering genetic, species, and community diversity in ecosystems.

WP1 STATE OF THE ART SCREENING

Characterizing Pharmaceutical Products (PP) pollution from anthropogenic and zoogenic sources in urban and rural European demo sites.



It is estimated that some substances reach significant emissions, up to 27 tons/year in urban areas (OECD, 2023)

The consumption of pharmaceuticals increased by 10% in the period 2019-2021 (OECD, 2023)

Advanced technologies are able to remove up to 90% of some molecules but with very high energy consumptions and costs (Aziz et al., 2025)

WP2 ASSESSING PP POLLUTION EFFECTS

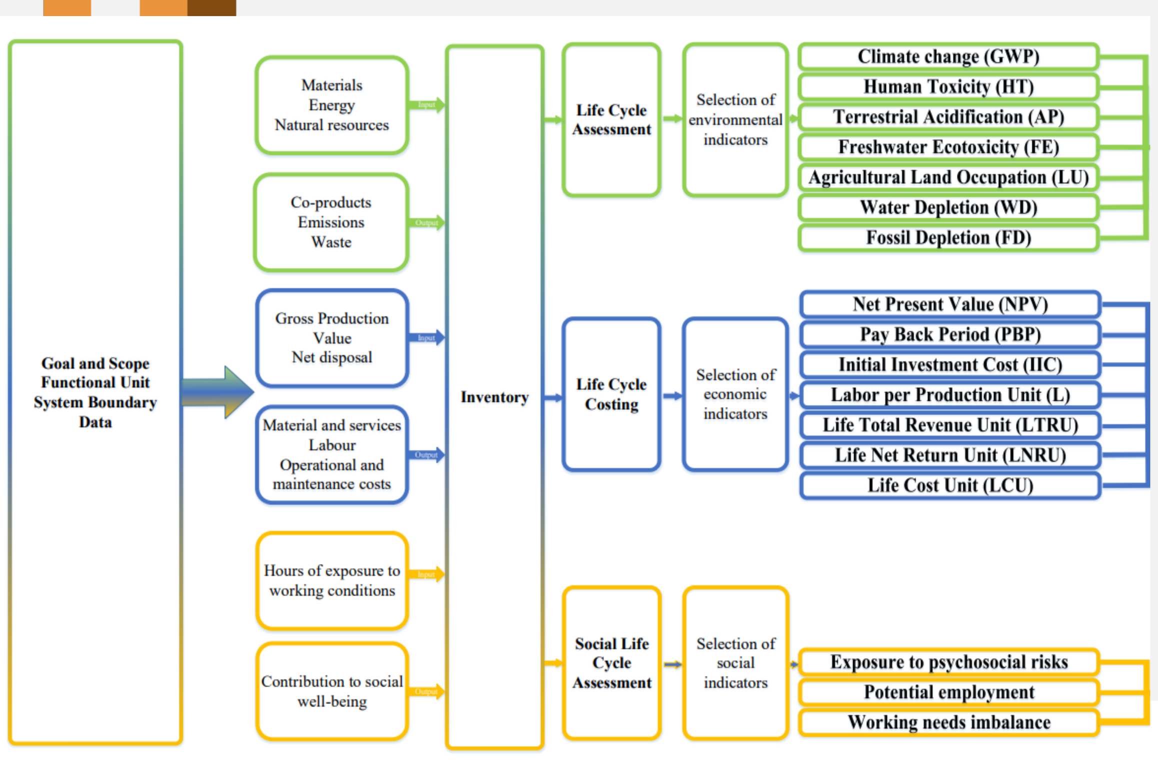
Assessing how aquatic biodiversity changes under PP pollution pressures through environmental DNA analyses

WP3 EFFECTIVENESS OF NbS IN POLLUTION REMOVAL

Assessing the effectiveness of the innovative NbS at pilot scale in PP pollution removal using chemical and ecotoxicological approaches.

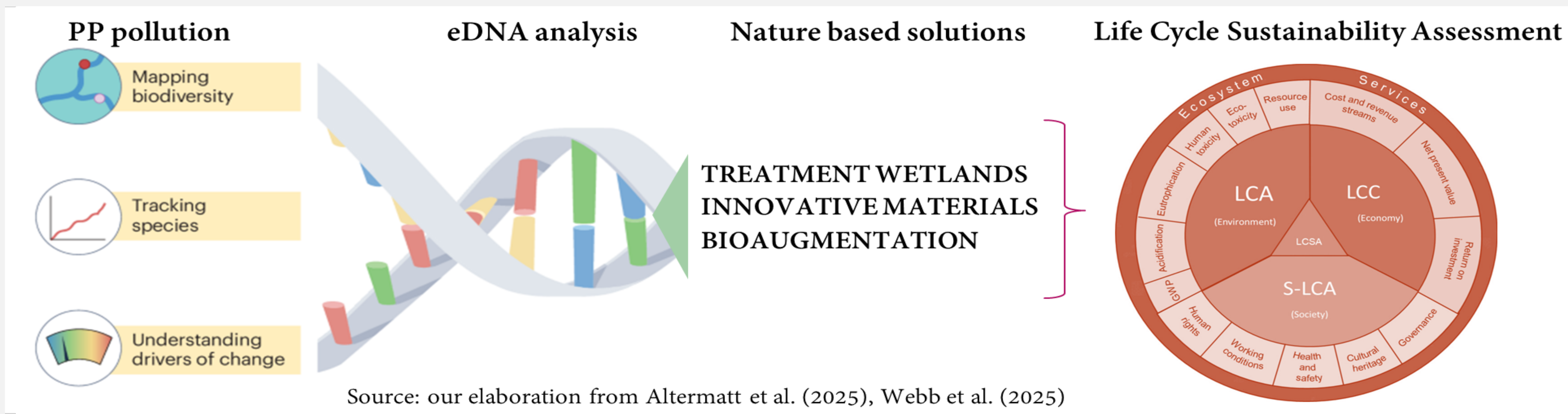
WP4 LIFE CYCLE SUSTAINABILITY ASSESSMENT

Understanding benefits and externalities associated with PP pollution mitigation by assessing the whole life cycle of NbS in terms of environmental, economic and social impacts and comparing them with business as usual treatments.



WP5 STAKEHOLDERS ANALYSIS

Assessing stakeholders' profiles, acceptance or conflicts around NbS.



Source: our elaboration from Altermatt et al. (2025), Webb et al. (2025)

WP4 RESEARCH QUESTION: WHICH ARE THE BEST NBS IN TERMS OF ENVIRONMENTAL, SOCIAL AND ECONOMIC SUSTAINABILITY WHEN CONSIDERING THEIR WHOLE LIFE CYCLE?

Life Cycle methodologies to evaluate the best NbS: WP4, leaded by UNIRC partner

While NbSs are potentially suitable to preserve ecosystem services and addressing sustainability challenges in urban and rural areas, their benefits need to be quantified, in terms of clear environmental, economic and social advantages, such as specific burdens, economic values and long-term cost-effectiveness. The aim is to evaluate the potential externalities linked to the implementation NBS for PP removal in terms of environmental cost or benefit, economic aspect feasibility and social repercussions related to human health. The following methods will be applied: Life Cycle Assessment (LCA), environmental and conventional Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA).

	LCA	LCC	SLCA
GOAL AND SCOPE	Selection of **technologies to be compared** to the Business-As-Usual (BAU) baseline scenario, e.g.: Treatment Wetlands (mimicking natural ecosystems), Innovative Materials (e.g. biochar and hydrochars), Bioaugmentation (i.e. increasing remediation capacity of active microbes), compared to a baseline scenario. Selection of the **Functional Unit**, i.e. the quantified measure of a product's or system's performance that serves as a reference for comparison: m^3 of wastewater treated or the mass (g) of target pharmaceuticals. Selection of the **system boundaries**: for example, from "cradle to grave", which includes planning, construction, transportation, maintenance, monitoring, end of life or recycling options. The **allocation procedures** consist of partitioning the input and/or output flows of a process to the product system under study; it can be based on physical allocation or system expansion in case of co-products. The **cut-off criteria** selection: they are thresholds used to exclude minor inputs, processes, or outputs from the study to simplify the analysis. Typically based on mass, energy, or environmental significance, they make the data collection and modelling process more manageable.		
LIFE CYCLE INVENTORY	**Secondary data**: specific LCA database (e.g. eco-invent V. 3.5) for the estimation of N_2O, nitrate leaching, etc. **Primary data**: interviews through a semi-structured questionnaire about remediation processes, flows of mass and energy, feedstock characteristics, process parameters, capital goods production, as well as waste process.	Main **cost items**, but also **financial data** of investment, classified as initial costs, operation and maintenance costs, operational costs, and end-of-life disposal costs or residual value.	**Working hours needs** per each life cycle operation, characteristics of the tasks, postures, and exposures of workers to different conditions (noise, dust, chemicals, etc.).
LIFE CYCLE IMPACT ASSESSMENT	**ReCiPe** (Huijbregts et al., 2016) assessment method using SimaPro software, that translates life cycle inventory data into environmental impact scores by linking emissions and resource uses to a comprehensive set of **midpoint** (problem-oriented) and **endpoint** (damage-oriented) indicators, enabling an integrated evaluation of impacts on human health, ecosystems, and resource depletion.	**Internal costs**: specific economic and physical parameters. Investment analysis: discounted life cycle cost (DLCC), Net Present Value (NPV), Internal Rate of Return (IRR), Gross Margin (GM), and Payback Period (PBP). **External costs**: environmental Prices approach (De Bruyn et al., 2018) using SimaPro software.	**Psychosocial Risk Factors impact pathway** (SLCA type II) to evaluate possible health risk for workers and local communities. Examples of impact categories: cancers, cardiovascular diseases, metabolic disorders, musculoskeletal disorders, neurological diseases, psychological stress, and respiratory diseases using SimaPro software.
LIFE CYCLE INTERPRETATION: expected WP4 results	**Systematically analysing and integrating** the environmental, economic, and social assessment results to identify key contributors, trade-offs, and improvement opportunities, supporting informed decision-making toward more sustainable design and operation of the NbS remediation technologies, compared to the Business-As-Usual (BAU) baseline scenario.		

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