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***ORIGINAL ARTICLE***

# Controlled microalgae culture as a reactive nitrogen filter: from ideation to prototyping

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***ABSTRACT***

Freshwater pollution caused by excessive reactive nitrogen in water due to extensive use of nitrogen-based fertilizers poses an ecological threat. As a result of an innovation management program, the problem is explored through the stages of research, ideation, solution (identification and validation), and prototyping/execution. After a description of the problem and a theoretical argumentation of the methodology used to approach it, each of these stages are discussed and the solution is presented. A water treatment module that grows microalgae for water purification and nitrogen recovery is proposed. Algae grown can be used as biomass material for animal nutrition, biofertilizers, and for the cosmetics industry.

*Keywords: Innovation management; nitrogen; eutrophication; microalgae; bioreactor.*

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## INTRODUCTION

Disturbance of the nitrogen (N) cycle brought about by human activities such as intensive agriculture is a known ecological problem. According to the Planetary Boundary Framework that defines Earth's safe operating zone, disruptions in N flows have already crossed the high-uncertainty threshold beyond which stretches a post-Holocene Earth - one that is much less suitable to human development (Steffen et al., 2015). Large-scale food production system is the main drivers of the global nitrogen imbalance (EU Nitrogen Expert Panel, 2015). In particular, excessive use of nitrogen-based fertilizers and inefficient manure management contribute to the emissions of reactive nitrogen species[1] such as nitrous oxide ($N_2O$), nitric oxides ($NO_x$), and ammonia ($NH_3$), which, when in excess, pose a threat to water and air quality, greenhouse gas balance, biodiversity, and soil quality (Sutton et al., 2011).

The non-binary (solved/not solved, wrong/not wrong) nature of the issue, its connectedness to other factors, and ultimately its relatively unknown scale make the nitrogen problem a "wicked" one. Therefore, it cannot be tackled solely using a technical approach (Rittel and Webber, 1973; De Leon et al., 2018). Although the problem is well recognized (UNEP, 2019), documented attempts of tackling it using methodologies that transcend a technology-driven approach are lacking, despite these methodologies having been recognized as useful in solving wicked problems in global challenges (Forster, 2004).

This paper tells the journey of an interdisciplinary team of MBA and PhD students in the design of a solution aimed at reducing reactive nitrogen pollution in freshwater using a transdisciplinary, non-linear, and design thinking-inspired approach. The project was carried out as a part of Innovation for Change, a 20-week open-ended innovation management program organized by IdeaSquare of CERN, Collége des Ingènieurs, and Politecnico di Torino. A description of the problem of reactive nitrogen pollution in freshwater is followed by a brief analysis of non-linear innovation and design thinking methodologies. We then discuss the application of these methodologies to the problem at hand, detailing our experience in each stage of the innovation process (research, ideation, solution (identification and validation), and prototyping/execution). Lastly, we describe our solution – a water treatment module that uses microalgae for water purification and nitrogen recovery and from which the algae yield becomes biomass for biofuel and biofertilizers.

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[1] For the purposes of this paper, reactive nitrogen will be referred to as N.

## THEORETICAL BACKGROUND

This chapter provides context to the problem space and the methods borrowed from non-linear innovation management used to tackle the problem. The first section discusses current opinions on methodologies used in non-linear innovation processes and the second provides details on N pollution.

### Non-linear innovation

A large portion of innovation happens linearly and incrementally. Linear innovation consists of three sequential steps: research → development → diffusion. After initial discovery in research facility, the idea is technologically developed in places with the necessary monetary resources. If proven scalable and profitable, it becomes a marketable product and is then distributed. Methods used in the stages of linear innovation are those typical of an industrial society: teamwork with each member depositary of specialized technical knowledge, incremental steps aimed at reducing uncertainty in the problem space, and a greater focus on problem solving than problem definition (Mehregany, 2018).

Non-linear (NL) innovation, also called irregular innovation, follows a different pattern (Shur-Ofry, 2016). Innovation stops being merely a cumulative and progressive process, confined within one discipline and controlled by specialists. Rather, it actively seeks to break up with existing conventions, gravitating close to paradigm shifts (Kuhn, 1970) and bringing about disruptive changes. In product development, these changes are followed by the creation of a new market pool and value network that affects people's perception of the environment in which such alteration arises, producing enormous socio-economic benefits. The value of innovations resulting from non-linear approaches is lower than conventional linear approaches; however, discoveries arising from non-linear innovation, although less frequent than those from conventional approaches, have an unexpectedly high value (Fleming, 2014.), making them particularly suitable to approach wicked problems of today's global challenges.

NL models of innovation require multi-disciplinary teams that pool their different skills sets (e.g. social design and industrial product development) and are willing and prepared for skill spillovers: using skills in areas that they are not commonly used in. These teams enjoy considerable freedom in the choice of their own sets of tools, which are usually quite diverse. They work iteratively in do-test-learn modes that ensure high learnability and use shorter steps in between the different stages (rapid prototyping is one important example). NL innovation management uses a large domain transfer (e.g. using the body to explore mental spaces, a technique also used in embodied learning (Meyer, 2012)). The most recent and powerful non-linear innovation methods are more human-centered (Utriainen et al., 2017).

### N-pollution and eutrophication

Intensive agriculture is one of the main contributors to N pollution. In particular, when N-based fertilizers in soil exceed the amount crops can absorb, the surplus percolates to aquifers, freshwater, and ultimately seawater. The excess of N, which is one of the key nutrients for plants growth, causes abnormal algae bloom – a phenomenon known as eutrophication (Harper, 1992). Water bodies with their surface covered with algae are deprived of sunlight causing the death of aquatic flora. Disposal of dead biomass thus produced allows proliferation of degrading aerobic bacteria which, consequently, cause hypoxia, a phenomenon wherein the low oxygen level in water or air becomes detrimental to the ecosystem. Water bodies then become inhospitable to basic life (fauna), leading to the death of bigger forms of life such as fish and amphibians.

### Microalgae as natural filters

Microalgae are microscopic algae whose size varies from ten to hundreds of micrometers (Jia & Yuan, 2016). They are found in both freshwater and marine habitats. 200,000 - 800,000 species exist, of which about 50,000 species have been catalogued (Starckx, 2012). This varied biodiversity makes microalgae one of the most important resources on the planet. Through photosynthesis, they provide roughly half the atmospheric oxygen. Moreover, they are responsible for fixing inorganic carbon to the soil and are a major source of omega-3s compounds (Adarme-Vega et al., 2012). Their growth rate exceeds ordinary crops by 5 – 10 times (Zullaikah, Utomo, Yasmin, Ong, & Ju, 2019). When combined with soil-less cultivation methods, they are an ideal source of sustainable alternative food.

In recent years, microalgae have been used to treat municipal, agricultural and industrial wastewater (Masojídek & Torzillo, 2008) as – in addition to filtering compounds such as dissolved metals, agricultural contaminants and exhaust gases – they are hungry for pollutants such as nitrates, phosphates, ammonia, and carbon dioxide, the main substances produced as a result of eutrophication.

Technologies using the filtering properties of microalgae to clean up contaminated water as classified as phytoremediation (Martinez-Porchas, Martinez-Cordova, López-Elías, & Porchas-Cornejo, 2014). Typically, phytoremediation takes place in bioreactors, i.e. controlled environments wherein algae grows in a constant water flow and the danger of algae spill out is prevented through a system of valves and filters. These systems are composed of transparent pipes (to allow sunlight for photosynthesis), filters, and water pumps. To allow optimum growing conditions, pipes should be 3 - 6 cm and 10 - 100 m in diameter and length respectively. Filters confine algae in the system, avoiding environmental dispersion, while water pumps provide fresh nutrients and oxygen through a constant flux (Muñoz & Guieysse, 2006).

In a typical nitrogen removal process using algae, ammonia is first turned into ammonium ions, then bacteria oxidize ammonia to nitrate, and lastly algae convert inorganic components into organic nutrients (Neori et al., 2004). Common microalgae cultures for freshwater recovery and nutrient removal, such as Chlorella, show high N uptake rate, and appear to be both efficient and cost effective when compared with chemical techniques (Patel, Barrington, & Lefsrud, 2012).

## PROCESSES AND METHODOLOGY

The following section describes the various stages of our journey and we discuss the methodologies borrowed from non-linear innovation management we adopted to find a solution for problem of reactive nitrogen.

### Early phase & the team

Our interdisciplinary team, composed of 5 people with different technical skills (a management, materials, aerospace, and electronics engineer and a neuroscientist), and interests (farming, open source communities, social impact measurement, team sports, and entrepreneurship). During the project, team members were not restricted to technical backgrounds and proven competencies, but brought their interests to the table as well. These interests became new skills and were useful when we needed to expand our thinking embracing diverse points-of-view simultaneously, something prophesized by, Mehregany (2018) and others.

### Research Phase

During the research phase we consulted various academic experts and industrial experts: the director of a public research institute on reactive nitrogen pollution; an expert of livestock nutrition from the UN Food and Agriculture Organization; the director of innovation of DSM, a Dutch multinational with large interests in the agricultural sector; a technician in the agricultural field expert in fertilizers among others. Other stakeholders involved in the problem such as farmers (from the UK, Italy, and Kenya), environmental associations, and inhabitants of the vicinity of polluted waters were also consulted with. Understanding the “human side” of the issue helped us better understand its complexity and develop a more rapid evaluation of possible solutions. At the beginning, we considered an educational program aimed at helping farmers optimize the amount of fertilizers used, but, after talking to a few farmers, we understood that most of them would have not accepted the behavioural change this would entail.

### Ideation phase

After gaining an understanding of the problem space, we brainstormed various ideas, without considering our technical expertise to allow an out-of-the-box thinking. In this phase, we used the following methods (some invented, some suggested to us by mentors, colleagues, and literature):

- freely letting our imagination contemplate, in particular, about the challenge in dystopian and utopian scenarios (Sørensen, 2006);
- applying one core technique from each member’s individual expertise to the challenge (e.g. - machine learning, aerodynamic modelling, or open-source software development);
- picking one aspect of the challenge (for example eutrophication) and answer “why” questions until a satisfactory level of depth into the problem was reached;
- playing a game called “Ideopedia” in which to a word related to the challenge another one had to be associated, and the association explained (Sgobba, 2017).

After several ideas were collected, we voted on the most promising one: “transferring agriculture away from the soil”, based on its practical and innovative appeal. We again conducted research through specialized literature and expert/stakeholders interviews, brainstormed on practical solutions, and further explored the idea space.

### Early technical and economical feasibility analysis phase & iteration

Ultimately, we identified five possible solutions of the idea we selected and we voted on them. We reached consensus on one (floating platforms), that was to be followed-up on with more research on its technical and economical feasibility. However, we realized that solution was not feasible (see Results section). In the meantime, partially repeating the steps of research and ideations phases, we arrived to a second solution, which we immediately started to prototype (see Results section). In this phase we applied the rapid changes and high adaptability that nonlinear innovation requires.

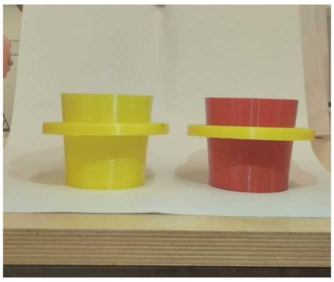

**Fig. 1.** The first 3D-printed prototype, which allowed us to understand we were after the wrong form

## Prototyping phase

As nonlinear innovation methodology recommends, we started prototyping as soon as we had a solution (Leifer and Steinert, 2011). At first, we found this a bit forced upon us, as we feared we were not ready yet. However, after a couple of failed/inappropriate prototypes (Fig. 1), we found this useful, as it allowed us to have a sense of "reality" and concreteness of the product we were developing. It also highlighted limitations and suggested improvement areas of our solution. The prototyping phase is discussed in the Results section.

## RESULTS

Two ways to solve the issue of nitrogen pollution are: decoupling the use of soil from agriculture, thereby reducing nitrogen leaks or absorbing excess nitrogen being leached to the waterways, thereby limniting the damage after the leak. The solution presented adopts both the approaches.

The first proposal was to grow nitrogen-hungry hydroponic plants or flowers on floating platforms, such as the one in Fig. 1. The plants would act as a nitrogen sink by absorbing excess N, whilst providing a substitute for the same plants or flowers grown on land that requires the introduction of NPK (nitrogen, phosphorus, potassium) through fertilizers. The floating platform would be made of buoys to allow floatability and a variable number of predisposed spaces in the middle, where plants could grow. Keeping modularity in mind, the platform was limited to 4 sq. m. to allow it to be adaptable to the curvature of the bank and to withstand waves. Plants roots would not directly be in contact with water, but a mechanical water distribution system, made of simple pipes and drippers would ensure the right amount of water and nutrients. Treated water could then escape the platform through another series of pipes.

However, issues with harvesting, maintenance, and complications resulting from a floating surface in a flowing river made this design unfeasible.

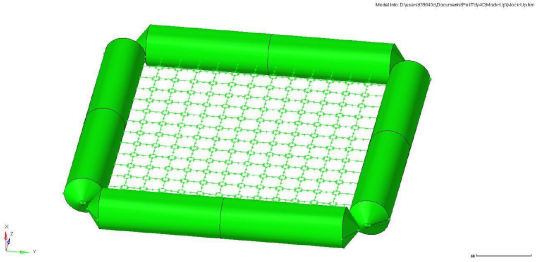

**Fig. 2.** Sketch of the freshwater floating platform

Hence, we propose growing algae in a series of bioreactors that are placed on dry land along the banks of rivers and lakes. The system would consist of pumps that would feed polluted water to the bioreactor. A mesh placed before the pump would stop objects such as plastic bottles, branches, fish etc. from clogging the system. An algae initiator would be placed inside a bioreactor to grow by absorbing dissolved nitrogen and other minerals, see Fig. 3. Clean water would then be passed through a series of filters to avoid the seepage of algae into the water body. Species native to the water body, typically Spirulina or Chlorella, would be used so as to not disturb the ecosystem balance. Algae has a higher N absorption rate as compared to other plants and it grows much faster. Considering an absorption rate of 25 mg/l, which is typical for Chlorella, and a bioreactor of 6 cm diameter and 100 m length, as suggested by the study mentioned earlier, 450 grams of N can be removed in 1 year, considering that the algae populates the entire bioreactor in 6 days (Jia, H., & Yuan, Q.). The bioreactors could be stacked vertically such as in Figure 3. A stack of 10 bioreactors would require an area of 5 sq. m and would be 2 m high.

**Fig. 3.** Bioreactor (Bioneer Greenenergy)

The approximate volume of the river Po in Italy, which is used as a case study, is 2,500 billion litres (Shiklomanov). Using a colorimetric system, N concentration in tap water and water from the Po river in Turin, was measured at approximately 10 mg/l and 25 mg/l respectively. Thereby, to clean the entire river in 1 year and avoid any excess leaching to the sea, we would need approximately 140 million bioreactor. Considering N is continuously added to the river over the year, it would take longer than 1 year. These bioreactors would be able to produce 25 million tonnes of algae to that can be used as animal feed or in the cosmetics and human nutrition supplement industry. The algae obtained will have to be harvested using different filtration methods such as centrifugation and microstraining.

The prototype currently being tested, Figure 4, involves a transparent PVC pipe that acts as a bioreactor, 2 sponges as the filters, 1 hose pipe and 1 battery powered 3D printed pump to circulate the water. As a pilot, we used aquatic plants to confirm the findings of the report by Jia, H., & Yuan, Q. that states that algae can remove 25 mg/l of N. We observed that after 7 days, the N concentration dropped from 25 mg/l to 10 mg/l in stagnant water. Since algae has a higher absorption rate, the findings in the report seem correct.

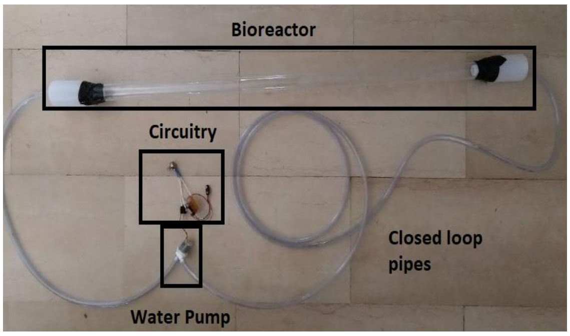

**Fig. 4.** Bioreactor prototype

## CONCLUSION

Leaching of excessive reactive nitrogen from farming activities into freshwater bodies poses a serious threat to the ecosystem and on everything that depends on it. As most environmental challenges, the problem of reactive nitrogen classifies as a wicked problem and it is best to solve it through non-linear innovation processes. In the context of a 20-weeks long innovation management program, our interdisciplinary team applied some of the most important methodologies of design thinking such as use of imagination, domain and skills-transfer, rapid iterations, and early prototyping etc. Our final proposal involves the introduction of microalgae into this polluted ecosystem. Microalgae, acting as natural filters, can absorb the reactive nitrogen in addition to other dissolved substances, whilst reducing carbon dioxide and increasing oxygen levels through photosynthesis. We calculated that, with our solution, microalgae can absorb almost 80% of the N present in the water through a series of bioreactors placed besides river and lake banks. As a case study, River Po in Northern Italy can be cleaned up using 140 million of these bioreactors using up approximately 150 sq km. of area and producing 25 million tonnes of algae that can be used in the animal nutrition, cosmetics, biofertilizer, or human nutrition supplements industry after due processing.

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