Nature-Inspired Principles for Sustainable Process Design in Chemical Engineering

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Abstract. Sustainable chemical processes should be designed to combine the technological advantages and progress with lower safety risks and minimization of environmental impact such as, for example, reduction of raw materials, energy and water consumption, and avoidance of hazardous waste and pollution with toxic chemical agents. A number of novel eco-friendly chemical technologies have been developed in the recent decades with the help of the eco-innovations approaches and methods such as Life Cycle Analysis, Green Process Engineering, Process Intensification, Process Design for Sustainability, and others. An emerging approach to the sustainable process design in process engineering builds on the innovative solutions inspired from nature. However, the implementation of the eco-friendly technologies often faces secondary ecological problems. The study postulates that the eco-inventive principles identified in natural systems allow to avoid secondary eco-problems and proposes to apply these principles for sustainable design in chemical process engineering. The research work critically examines how this approach differs from the biomimetics, as it is commonly used for copying natural systems. The application of nature-inspired eco-design principles is illustrated with an example of a sustainable technology for extraction of nickel from pyrophyllite.

Keywords: Nature-Inspired Principles, Sustainable Technology, Process Design, Eco-inventive Principles, Chemical Engineering, Biomimetics

1 Introduction

Chemical Engineering sector is essential to human well-being, but it also contributes to the degradation of ecosystem goods and services that are important to sustain all human activities. In order to promote sustainable development, chemical engineering must solve this contradiction by developing chemical products and processes that meet the needs of present and future generations. Sustainable chemical processes should be designed in such a way that the processes must use raw materials, energy and water as efficiently and economically as possible in order to avoid the generation of hazardous waste and to preserve the reserves of raw materials [1]. The processes must use the least amount of energy that is economical and feasible, both to avoid the accumulation of carbon dioxide in the atmosphere from burning fossil fuels and to preserve fossil fuel reserves. Water must also be consumed in sustainable amounts that do not affect the quality of the water source and its long-term reserves. All aspects of chemical processing should include appropriate health and safety regulations. Aqueous and atmospheric emissions must not be environmentally harmful and solid waste in landfills must be avoided. Start-up, emergency stop and ease of use are other important factors. Flexibility, the ability to cope with different conditions (such as different raw materials and product specifications) may be important. Higher operational availability, measured in operating hours per year, is also of crucial importance.

In the past few decades, a number of new green chemical technologies have been developed using eco-innovation approaches and methods such as life cycle analysis [2], green process engineering [3], process intensification [4], process design for sustainability [5] and others. However, the implementation of green technologies is often associated with secondary problems with corresponding primary and secondary eco-contradictions. A primary eco-engineering contradiction occurs when the improvement of a non-ecological engineering parameter (e.g. process yield) leads to a deterioration of an environmental characteristic (e.g. water consumption), or vice versa. A secondary eco-contradiction is a situation where the improvement of one ecological parameter causes the worsening of another ecological parameter [6].

Nowadays, a promising approach to sustainable innovation based on innovative solutions that are inspired by nature is defined as biomimetic or bio-inspired eco-design. Numerous innovations in biomimetic databases, for example the AskNature database of the Biomimicry Institute [7] are available for design inspiration. However, in the biological-inspired design process, there are still great limitations in finding the most suitable biological resources to solve technical problems due to the huge size of the information database and the lack of adequate guidance for engineers on how to conduct biological research. It is not surprisingly, that substantial biomimetic or bio-inspired designs methods are supported by the numerous analytical and creativity tools, for example tools derived from the theory of inventive problem-solving TRIZ [8, 9]. The TRIZ methodology [10, 11] is currently an important part of knowledge-based innovation and is one of the most comprehensive and systematic methods of creative thinking and inventive knowledge [12], as only TRIZ offers methods and abstract solution principles for identifying and eliminating engineering contradictions and dramatically improves the ingenuity of engineers. For example, our latest research on ecological innovation in process engineering [13, 22] proposes the substantially extended version of 40 TRIZ Innovation Principles with 160 sub-principles and outlines 23 most reliable invention sub-principles for solving environmental contradictions. The proposal is based on an analysis of 100 ecological patents, 58 process enhancement technologies and literature. However, most new ecological solutions still contain minor secondary ecological contradictions.

In summary, it can be assumed that although the product and technological design could be inspired by nature, man-made products or technologies still cause many ensuing problems. On the other hand, the existing natural systems should have less additional environmental impact [6]. Natural systems consist of a dynamic and complex set of components and systems that interact, lead to new behavior, and perform tasks that ultimately aim at survival, which is roughly reflected in the maintenance of current activities. Such activities include processing matter and energy, transporting fluids, changing phase state to obtain products of high quality, and communication. The similarity is striking with what processes in chemical engineering are intended for, since they also deal with the processing of matter, energy and data [14]. Thus, the extraction of underlying abstract eco-inventive principles used in the nature could be helpful for problem solving. These inventive biological principles found in biological systems are referred to herein as "natural inventive principles" [6] or “nature-inspired principles”.

In this context, the ultimate goal of the research presented in this paper is to postulate that the eco-inventive principles identified in natural systems allow to avoid secondary eco-problems in new products or technologies. The paper proposes to apply these principles for sustainable design in chemical process engineering. The research work critically examines how this approach differs from the biomimetics, as it is commonly used for copying natural systems. The application of nature-inspired eco-design principles is illustrated with an example of a sustainable technology for extraction of nickel from pyrophyllite.

2 Nature-Inspired Inventive Principles for Eco-Innovation

Working with nature can pave the way for a greener, more competitive, energy- and resource-efficient economy. From the nature perspective, instead of developing new innovation with new functionality, we should learn and adapt the materials we have from nature. Nature was always a source of inspiration for innovation and has led to several scientific design approaches. As stated in our recent study [6], in addition to reviewing the literature, the natural principles for ecological innovation can also be identified in technological solutions inspired by nature and in natural ecosystems.

The identification of natural principles can be performed by combining different complementary approaches: firstly, retrieval and analysis of existing bio-inspired eco-friendly technologies and of the corresponding biological solutions, for example in the AskNature database of the Biomimicry Institute [7], followed by identification of the abstract natural solution principles. Secondly, it could be done applying the problem-driven approach: search for biological solutions for existing environmental problems using various algorithms, for example, the Function-Oriented Search for bio-inspired design [15] or the Unified problem-driven process of biomimetics [16]. Lastly, the solution-driven approach can be proposed for identification of the eco-systems existing in unfavorable environment or under temporary environmental stress, analysis of existing biological solutions, and selection of the eco-engineering problems to which biological solutions could be applied.

2.1 Natural Inventive Principles Identified from Bio-Inspired Design

The natural principles discovered from eco-friendly technologies can be analyzed in existing biomimetic databases such as, for example AskNature [7], a database of the Biomimicry Institute. AskNature is successfully establishing tools within the bio-inspired design toolset [17]. Known for being the largest database related to bio-inspiration, it aims at initiating pathways between natural phenomena, living organisms resenting such phenomenon and potential experts of considered organisms [18]. In this study, we retrieved some bio-inspired design examples from the AskNature database, as shown in Table 1.

Table 1. Examples of eco-innovations inspired by nature, retrieved from [17].

No	Bio-inspired design example	Description
1	Eco-machine wastewater management	Custom-built wastewater treatment system purifies water without chemicals by mimicking a natural ecosystem
2	Biohaven floating islands	Water filtering system mimics marshes
3	Vortex generator watreco	Trout inspires water treatment system
4	Green infrastructure storm water control	Storm water management mimics nature
5	Solar water still and pump	Solar pump purifies water inpired by a tree tranpires
6	Elf shelter rainwater collector	Rain water collector mimics leaf
7	East Gate Centre	Passive and low-energy building heating and cooling inspired by models of internal temperature regulation in termite mounds
8	Vertical farming	Agriculture system for environment in the city
9	The land institute permaculture	Perennial grain cropping or permaculture mimics natural ecosystem through development of mixed crop perennials
10	Biolytix water filter	A compact waste treatment system that converts raw sewage, wastewater, and food waste into high quality irrigation water on site

The corresponding biological solutions and abstract principles of the biological solutions in the 10 ecological designs were analyzed. Table 2 exemplarily presents an incomplete fragment of the component and function analysis of the Eco-machine waste water management [23], corresponding to the phase 1 of the proposed solution driven approach to bio-inspired design outlined in our latest study [6]. Each function is a subject of further analysis, which results in the identification of biological solution principles. Similar to the matrix of ecological requirements presented in [6, 19], analyzing correlation matrix of the identified functions will allow to systematically identify resolved contradictions and synergies between the functions in the bio-inspired design process.

Table 2. Fragment of the component and function analysis of the Eco-machine [23] waste water management.

System Level		Eco-function	Natural inventive principles
Super system	A custom-built wastewater treatment system	Water purification using sunlight, biodiversity and natural processes	Utilize natural processes Increase the level of biodiversity. Use of sun radiation.
System	A series of aquatic tanks	Aquatic tank as wetland ecosystem and contain organisms from all five kingdoms of life	Increase the level of biodiversity.
Sub-systems	Bacteria	Breaking down waste and organic materials	Use microorganisms.
	Native plants and organisms	Utilizing broken down materials as nutrient cycle	Utilize waste resource.

In summary, all identified natural principles found in 10 bio-inspired designs mostly utilize natural processes by increasing the level of biodiversity and using the microorganisms instead of using hazardous chemicals which can be harmful to the environment and ecosystems.

2.2 Natural Inventive Principles Identified from Natural Ecosystems

Natural ecosystem is an ecosystem which occurs naturally and can survive without any intervention from human beings where organisms freely interact with other components of that environment. Some examples of identified natural ecosystems existing in unfavorable environment are shown in Table 3 and were analyzed in search for nature-inspired inventive principles in a same way as in the Section 2.1. Living in the hostile environment brings serious challenges to the natural eco-systems and requires their adaptations.

Table 3. Examples of natural eco-systems existing in unfavorable environment.

No	Natural ecosystem	Description
1	Mangroves	Salt-tolerant trees, adapted to life in harsh coastal environment under the low oxygen conditions of waterlogged mud.
2	Rainforest	Area of tall, mostly evergreen trees and a high amount of rainfall.
3	Grassland	Area almost continuous covered by grasses, without many taller plants.
4	Oasis	Area made fertile by a source of freshwater in an otherwise dry and arid region.
5	Coral reef	Underwater fragile ecosystem characterized by reef-building corals, sensitive to water conditions.
6	Taiga	Boreal or snow forest of the cold, subarctic region.
7	Arctic Tundra	Type of biome where the tree growth is hindered by frozen subsoil, low temperatures and short growing seasons.
8	Antarctic life	Thriving ecosystems on land and in the water: dry, extremely cold, windy, 24 hours of dark winter.
9	Son Doong cave	Formed in soluble limestone intricate cave system created by water, measuring more than 5 km long, 200 metres high and 150 metres wide.
10	Mariana Trench	Deepest point on earth with many unique environments (volcanoes and marine life forms).

Table 4 presents an illustrating fragment of the component and function analysis of the mangroves eco-system [6]. The mangroves are salt-tolerant trees, which are adapted to life in harsh coastal environment under the low oxygen conditions of waterlogged mud. They contain a complex salt filtration system and complex root system to cope with saltwater immersion and wave action. Dead mangrove leaves and branches, broken down by microorganisms before it is made available to the food chain, add nutrients to the tidal creek [24]. Mangrove roots also trap plant material such as seagrass which adds more nutrients to the system. The remaining organic matter of sea life, such as crustaceans, snails and small fish, is taken up by the roots of the mangroves. Mangroves colonies also anchor shore-lines and act as a coastal buffer zone between land ecosystems and sea [20].

Table 4. Fragment of the component and function analysis of the mangroves eco-system [6].

System level		Eco-function	Natural inventive principles for eco innovation
Super Sys-tem	Mangro-ves colony	Buffer zone between land and see; anchoring shorelines; protecting coral reefs from sedimentation; capturing carbon dioxide	Roots reduce turbulences in coastal barrier structures [20].
Sys-tem	Mangrove tree	Nurseries and food source for marine life; attracting living organisms to the eco-system	Increase the level of biodiversi-ty. Attract bio-resources. Use microorganisms in hostile environment
Sub-sys-tems	Pneumat-ophores	Absorbing oxygen from the air and water (pipe-like structures sticking out of the mud act like snorkels)	Simultaneous absorption of substances from gas and fluid.
	Roots and stems	Mangrove roots and stems have special tissues which act as a barrier to salt	Use in parallel different tech-nologies (in root and leaves) to block or extract harmful agent.
	Fresh leaves	Extraction of the salt underneath the mangrove leaves (special glands concentrate salt and ex-crete it to the surface)	Use different sides or parts of an object for competing opera-tions: extraction of salt and photosynthesis.
	Leaves, flowers, fruits	Concentrating and removal the salt: salt can be moved to old leaves, flowers, tree bark or fruits which then drop off, taking the concentrated salt with them	Apply biodegradable waste to remove harmful substances.
	Seeds	Protect reproductive function from environment: seedlings germinate, and start developing on the tree and can survive in seawater for year or more	Isolate sensitive biological processes from hostile envi-ronment.

3 Application of Natural Inventive Principles in Chemical Engineering – a Case Study

The application of natural inventive principles for eco-innovation is illustrated with an example of a sustainable technology for extraction of nickel from pyrophyllite. Figure 1 shows a froth flotation process of nickel from ore applied by several mining industries. Froth flotation is a method used to recover base metals like copper, zinc, and molybdenum from sulfide ores. The slurry from the grinding mills is mixed with chemical frothers and collectors in large tanks. Air is injected into the bottom of the tank to create bubbles. The bubbles are the key to separating the mineral from waste rock sand (tailings). The mineral sticks to the bubbles and rises to the top of the tank, while the tailings fall to the bottom. The froth is collected and a sent through a series of thickeners to remove the water. The material collected at the end of the froth flotation process is called mineral concentrate.

Nickel, as a strategic reserve metal, is not only a threat to the sustainable development of the economies but also a potential major factor to the national security. As an important metal, nickel is widely used in stainless steel and new material industries. Nickel is recovered through extractive metallurgy: it is extracted from its ores, for example Pyrophyllite, by concentration through a froth flotation process followed by pyrometallurgical extraction. First, chemical agent as solvent extraction is added into ores before the froth flotation process. The solvent is used to separate nickel from the ores. The nickel extraction using this method has a significant nickel concentrate.

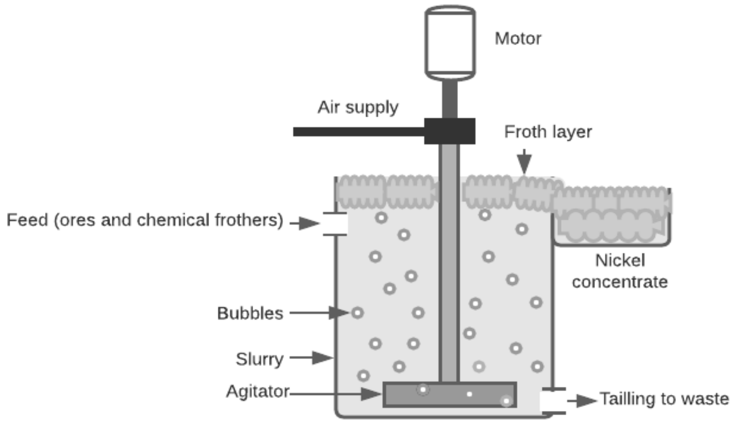

Fig. 1. Froth flotation of ores containing nickel.

In sustainable point of view, the using of chemical agent for nickel extraction will be a difficult question to answer. Fewer than 20 nickel mines around the world dispose of their waste into the sea (known as deep-sea tailings disposal, or DSTD), home to the highest diversity of corals and reef fishes. Companies often choose DSTD as a cost-efficient or safer option to manage tailings, the byproducts left over from extracting metal from ore. It is an alternative to constructing a dam to store the tailings or spending money to treat the waste so it can be returned to the ground. In fact, submarine tailings disposal is a harmful, outdated practice that decimates marine life and destroys the livelihoods of fishing-dependent communities. In this study we tried to apply the identified natural inventive principles for designing the sustainable nickel extraction technology.

The analysis of environmental issues and the application of appropriate natural principles in eco-friendly process design is presented in Table 5. The method starts with a comprehensive analysis of environmental issues, including understanding the basic functions of the equipment, its operation, the environment, and the operating conditions of each level of the system (super system, system, and subsystem). Function analysis and process mapping techniques [21] lead to the identification of useful functions and undesirable properties of unit operations. Identification of the key negative effects of the analyzed system in accordance with the principles of Cause Effect

Chain Analysis and Root-Conflict Analysis RCA+ helps to identify the root causes of problems and to rank them accordingly the objectives of process design.

Table 5. Problem-driven bio-inspired design process.

	Phase	Description	Tools
I. Problem analysis	1	Analysis of the eco-problems and identification of primary and secondary eco-contradictions	Function Analysis & Process Mapping [21], Root Conflict analysis RCA+
	2	Translation into 14 environmental impact categories	Correlation matrix of ecological requirements [22]
II. Selection and application of relevant natural principles	3	Identification of the biological solutions and extraction of the and natural inventive principles	Modified solution-driven process of bio-inspired design [6]
	4	Search for engineering domains and problems for application of natural inventive principles	Correlation matrix of ecological requirements [22]
	5	Creative and systematic idea generation	Natural inventive principles. Elementary TRIZ principles for eco-innovation [22]
	6	Creation and optimization of the innovation eco-solution concepts	AIDA concept design and optimization approach [21]

The problems are translated into 14 environmental impact categories [22]: Acidification, Air pollution, Chemical waste disposal, Depletion of abiotic resources, Energy consumption, Eutrophication, Ozone layer depletion, Photochemical oxidation, Radioactivity, Raw material intensity, Safety risks, Solid Waste, Toxicity, Water pollution and others. These categories not only can be used to identify possible secondary ecological contradictions, but also helps in the selection of the relevant natural principles. The correlation matrix of interactions with 14 environmental categories that are most relevant in the process engineering proposed by authors [22], helps to see how an improved eco-parameter can have a positive or negative effect on the other eco-parameters, and to check whether a biological system offers the same properties as an engineering one. Furthermore, specific engineering problem incl. possible primary and secondary eco-engineering contradictions are also taken into consideration for application of the proposed approach.

Table 6 shows the examples of ecological problems in the existing nickel flotation technology tackled by natural principles approach. Figure 2 illustrates the possible experimental design realization for nickel extraction from Pyrophillite ores after applying natural inventive principles to the froth flotation. The slurry from the grinding mills is mixed with organic solvent instead of hazardous chemical agent. Furthermore, the tailings are recycled to the feed and the remaining ores are putting back to the ores came from.

Table 6. Application of natural inventive principles for sustainable nickel extraction.

System level	Eco-problems	Applied natural inventive principle	Possible experimental realization
Super system	High chemical waste generation from nickel extraction	Use natural material or biological process	Use water for slurry instead of chemical
System	Chemicals frothers used to separate nickel from ores	Use natural material or microorganisms. Apply biodegradable waste to remove harmful substances.	Use organic solvent or microorganisms instead of hazardous chemical agent
Sub-system	Chemical waste disposal from nickel extraction	Utilize waste resources.	Recycle tailings back to the feed and tunnels the ores came from (material cycle)

A unit operation can be seen as sub-system which interacts in an eco-system or the process. Therefore, the proposed approach is also well suited for direct application in process scale. However, it is still necessary to break down the complete production process into unit operations for anticipation of possible new secondary problems and eco-contradictions as well as thermodynamic equilibrium in each component. A thermo-dynamic system is in thermodynamic equilibrium if the system is in mechanical, thermal, and chemical equilibrium simultaneously. In thermodynamic equilibrium, there is no tendency for a change of state to occur, neither for the system nor for its surroundings. Therefore, these additional limitations should be taken into consideration for selection of natural principles.

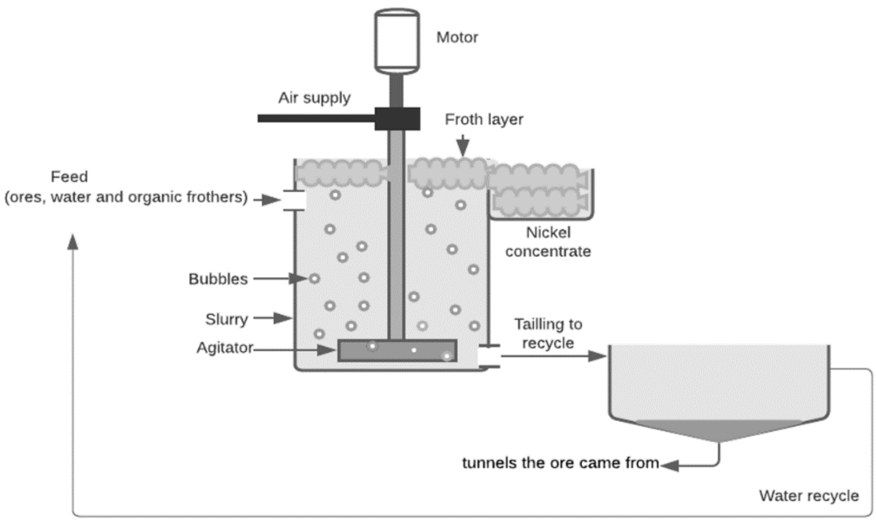

Fig. 2. Possible experimental design of nickel extraction using froth flotation.

4 Concluding Remarks and Outlook

Sustainable chemical processes must be designed in such a way that processes must use raw materials, energy, and water as efficiently and economically as possible in order to avoid the generation of hazardous waste and to preserve raw material stocks. The study postulates that the eco-inventive principles identified in natural systems make it possible to avoid secondary eco-problems and suggests applying these principles to sustainable design in chemical engineering. The study outlines that the natural principles identified in natural eco-systems and bio-inspired innovative designs mostly utilize natural processes by increasing the level of biodiversity and using the microorganisms and biodegradable substances for different tasks instead of using hazardous chemicals. Furthermore, the application of identified natural principles to the chemical processes such as nickel extraction from ores (Pyrophyllite) will help to improve the ecological problems faced by the current technology without causing secondary eco-problems. However, the real positive environmental impact of proposed experimental design is not yet fully investigated in practice. Moreover, the future scientific work should be focused on identification and systematization of other natural eco-innovative solutions and on the analysis of correlations between the underlying natural inventive principles.

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