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Eco-Feasibility Study and Application of Natural Inventive Principles in Chemical Engineering Design

Mas'udah¹[0000-0003-4335-7715], Pavel Livotov²[0000-0001-8784-1117], Sandra Santosa¹, Arun Prasad Chandra Sekaran³, Anang Takwanto¹, Agata M. Pachulska²

¹ Politeknik Negeri Malang, Jl. Soekarno Hatta No. 9, 65141 Malang, Indonesia

² Offenburg University of Applied Sciences, Badstr. 24, 77652 Offenburg, Germany

³ iFluids Engineering, 20, Seventh cross street, Shenoy Nagar West, Chennai, 600030, India
masudah@polinema.ac.id

Abstract. The early stages of the front-end process development are critical for the future success of projects involving new technologies. The application of eco-inventive principles identified in natural systems to the design of chemical processes and equipment allows one to find ways to mitigate or avoid secondary ecological problems such as, for example, higher consumption of raw materials or energy, generation of hazardous waste and pollution of the environment by toxic chemicals. However, before implementing a new technology in a real operational environment, it is necessary to completely investigate its undesirable ecological impact and to evaluate the future viability of this technology. Therefore, the research paper presents a study of ecological feasibility of an innovative process design utilising natural eco-inventive principles and analyses the correlations between applied inventive principles. Such eco-feasibility study can be considered as an important decision gate to determine whether the technology implementation should be moved forward. Furthermore, the study evaluates the practicability of natural inventive principles to the eco-friendly process design and is illustrated with an example of a sustainable technology for nickel extraction from pyrophyllite.

Keywords: Eco-inventive Principles, Nature-inspired Innovation, Feasibility Study, Chemical Engineering, Process Design, TRIZ

1 Introduction

The field of chemical engineering is essential for human life, but it also contributes to the deterioration of ecosystem products and services that are important for maintaining the activity of all human beings. For sustainability, chemical processes must be designed to use raw materials, energy and water as efficiently and economically as possible in order to avoid the generation of hazardous waste and conserve raw material reserves [1]. In addition to raw material, energy and water consumption, all aspects of chemical processing must include appropriate health and safety standards. Aqueous and atmospheric emissions must not be harmful to the environment and solid waste in landfills must be avoided [2].

Today, learning from nature is a promising approach for sustainable innovations, where chemical processes and operations can be designed by taking more inspiration from the existing biological systems. Nature has always been an inspiration for innovation and has led to a number of scientific design approaches. A number of new green chemical technologies have been developed using eco-innovation approaches and databases such as Ask Nature from the Biomimicry Institute [3] available for design inspiration. Unfortunately, many examples of what is popularly referred to as biomimicry or biomimetics resort to superficial analogies, duplicating nature, creating similar geometries, or reproducing isolated features that appear attractive, but all too often ignore the actual underlying mechanisms or context. As a result, the copying nature leads to suboptimal results. Not surprisingly, substantial biomimetic methods are supported by numerous analysis and creativity tools, for example tools derived from TRIZ, inventive problem-solving theory [4, 5]. The TRIZ methodology [6, 7] provides abstract solution principles and methods for identifying and eliminating engineering contradictions and helps to dramatically improve the inventive abilities of engineers.

The Nature-Inspired Chemical Engineering (NICE) methodology, developed in the recent decade by Coppens and co-workers [1, 8], is based on nature-inspired fundamental mechanisms to solve chemical engineering problems. The NICE approach provides a systematic platform to innovate and share the transforming technologies needed to tackle major challenges, including sustainability. Assisted by theory and experimentation, NICE aims to innovate, guided by nature, but does not mimic nature. The principal four themes for NICE consist of (T1) hierarchical transport networks; (T2) force balancing; (T3) dynamic self-organisation; and (T4) ecosystems, networks and modularity [8]. These themes include concepts related to fundamental mechanisms that are ubiquitous in nature, grouped by properties that are also critical to applications. The recent paper on this nature-inspired solution (NIS) methodology provides more examples relevant to chemical Process Intensification [8]. It facilitates the scaling of bubbling gas-solid fluidized beds, making their operation smoother and more controllable regardless of scale. Fluidized beds are widely used in chemical processes such as catalyst manufacturing, incineration, gasification, drying, coating and other industrial processes.

Similar to the NICE methodology, our recent studies [2, 9] have shown that working with nature can pave the way to a greener, more competitive, energy- and resource-efficient economy. Observing natural systems helps us discover the enablers that underpin the behaviour of complex systems. There, the principles can be applied to the design of industrial processes to achieve resilience and efficiency. The research work highlighted that the natural principles identified in natural ecosystems and innovative bio-inspired designs mainly utilise natural processes that increase the level of biodiversity, use microorganisms and biodegradable substances for various tasks instead of using hazardous chemicals. The study [2] was illustrated with an example of development of a sustainable process design for nickel extraction from pyrophyllite. It showed that the application of inventive principles identified in natural systems for chemical processes helped to improve the ecological problems faced by current technology. However, the study had not yet fully explored actual positive environmental impacts as well as had not investigated the ecological feasibility (eco-feasibility, for short) of the proposed experimental design in practice.

The eco-feasibility study should help to anticipate and to avoid secondary environmental problems of a novel technology. It can be performed in one of the early phases of the front-end process development and is crucial for the sustainability and future success of projects. Furthermore, besides evaluating the environmental impact and viability of the proposed technology, the eco-feasibility study can also be used to investigate whether the natural eco-inventive principles implemented in the process design can solve all the environmental issues faced by the prior technology without inflicting secondary ecological problems. In addition, the results of the eco-feasibility study can be used to analyse the relationships between the natural principles applied in the design. From there, it can be determined which combination of natural principles addresses most environmental issues. Also, the practicability of applying natural eco-inventive principles to process design can be assessed.

Therefore, the main objective of this paper is to present an ecological feasibility study of the process design using natural eco-inventive principles and to analyse the correlations between the applied inventive principles throughout the production process. This research is a follow-up to our previous work [2] and is illustrated with an example of further development of nickel extraction from pyrophyllite using a froth flotation process that implements the natural eco-inventive principles. Even though the case study in this research uses an example of nickel recovery from pyrophyllite ores, it also can be applied to any chemical process with similar eco-problems. The ecological impacts of any innovative process design must be fully investigated to assess the feasibility of the proposed technology before its realisation in a specific operating environment. Thus, the eco-feasibility study can be considered as an important decision gate to determine whether the technology implementation should be moved forward.

2 Eco-Feasibility Study of Application of Natural Eco-Inventive Principles in Chemical Engineering Design

2.1 A Case Study – Froth Flotation of Nickel from Pyrophyllite Ores

Froth flotation is a process used to recover base metals such as nickel, copper, zinc, and molybdenum from sulphide ores. A chemical agent such as solvent extraction is usually added to the minerals prior to the froth flotation process. The solvent is used to separate metals from minerals. As our recent study [2] has shown, the use of chemical agents in froth flotation is a major threat to sustainable development. Fewer than 20 metal mines worldwide such as nickel mines dispose of their waste in the ocean (known as Deep Sea Tailings Disposal or DSTD), which is home to the greatest diversity of coral and reef fish. In fact, underwater waste disposal is a harmful and outdated practice that is destroying marine life and destroying the livelihoods of communities that depend on fishing.

In this case study, we have analysed the environmental issues in the existing process technology and applied natural inventive principles for designing the new complete production of sustainable nickel extraction from pyrophyllite. The problems analysis and selection of appropriate natural principles presented in Table 1 and Table 2 was

carried out based on a problem-driven bio-inspired design process [2]. The problem analysis in the current technology as presented in Table 1 began with a comprehensive analysis of environmental issues, including an understanding of the basic functions of the equipment, its operation, the environment and operating conditions using Root conflict analysis RCA+, Function Analysis and Process Mapping [10]. The identified eco-problems in the current process technology then were translated into environmental impact categories in accordance with [11]: 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. With the help of correlation matrix of ecological requirements, an empirical tool proposed by the authors in [11], the classification of the identified eco-problems can help to select relevant natural eco-inventive principles and also to forecast possible secondary ecological concerns.

Table 1. Eco-problems in the existing technology of nickel recovery from pyrophyllite.

System level	Eco-problems	Category
Super system	Toxicity of chemical collectors	Toxicity
System	High chemical waste generation in the tailing solutions	Chemical waste disposal
Sub systems	High energy consumption for aeration due to long process	Energy consumption
	High dust generation during the process	Air pollution
	Ocean acidification due to DSTD system	Acidification
	High possibility of dust inhalation during the process	Safety risks
	Mining for minerals/ contamination of resources	Depletion of abiotic resources
	Waste disposal containing phosphate contaminates the water which potentially causes eutrophication	Eutrophication, Water pollution
	Chemical agents such as hydrogen cyanide can volatilize during the process and potentially react with the sunlight and cause photochemical oxidation.	Photochemical oxidation, Ozone layer depletion
	Harmful underwater waste disposal	Water pollution
	High reagent consumption	Raw material intensity
	High solid waste in tailing product	Solid waste

The selection and application of relevant natural eco-inventive principles, as presented in Table 2, was based on the identification of biological solutions and the extraction of natural eco-inventive principles using the modified solution-driven process [9]. The natural principles, assigned to the pre-defined eco-categories, were incorporated into a nature-inspired solution concept and then into a formulated process design for an intended use. The last step includes the creation and optimization of the sustainable solution concepts, followed by prototyping with experimental realisation according to the Advanced Innovation Design Approach AIDA [10].

Table 2. Experimental results of applying natural eco-inventive principles for nickel recovery.

Eco-problem categories	Applied natural eco-inventive principles	Experimental realisation	Experimental results
Toxicity	A. Use natural materials	Use organic solvent or microorganisms instead of hazardous chemical agent	Very low ecological impact, no mitigation of eco-impacts required
	B. Use microorganisms		
Chemical waste disposal	A. Use natural materials	Use water for slurry instead of chemicals	Very low ecological impact, no mitigation of eco-impacts required
	C. Utilise waste resources	Reuse the water for feed in	
Energy consumption	D. Use in parallel different technologies	Use parallel different technologies to speed up the process	Moderate ecological impact, minimal and effective mitigation of eco-impact possible
Air pollution	E. Simultaneous absorption of substances from gas / fluid	Absorbing dust from the air	Low ecological impact, minimal and effective mitigation required / possible
Acidification	C. Utilise waste resources	Recycle tailings back to the feed and tunnels the ores came from (material cycle)	Very low ecological impact, no mitigation of eco-impacts required
Safety risks	E. Simultaneous absorption of substances from gas / fluid	Absorb dust from the air	Low ecological impact, minimal and effective mitigation required / possible
Depletion of abiotic resources	F. Use different parts of an object for (competing) operations	Extract part of minerals containing desired metal	Moderate ecological impact, minimal and effective mitigation of eco-impact possible
Eutrophication, Water pollution	A. Use natural materials	- Use organic material instead of hazardous chemicals	Low ecological impact, minimal and effective mitigation required / possible
	C. Utilise waste resources	- Recycle tailings back into the feed and tunnel where the minerals come from	
Photochemical oxidation, Ozone layer depletion	A. Use natural materials	Use organic solvent or microorganisms instead of hazardous chemical agent	Low ecological impact, minimal and effective mitigation required / possible
	B. Use microorganisms		
Water pollution	C. Utilise waste resources	Recycle tailings back to the feed and tunnels the ores came from (material cycle)	Low ecological impact, minimal and effective mitigation required / possible
Raw material intensity	A. Use natural materials	Use organic solvent or microorganisms instead of hazardous chemical agent	Low ecological impact, minimal and effective mitigation required / possible
	B. Use microorganisms		

Solid waste	C. Utilise waste re-sources	Recycle tailings back to the feed and tunnels the ores came from (material cycle)	Low ecological impact, minimal and effective mitigation required / possible
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Figure 1 illustrates the process flow diagram of the experimental embodiment for the froth flotation of nickel from pyrophyllite ores after applying natural eco-inventive principles. The sludge from the mills was mixed with organic solvents instead of dangerous chemicals. Then the flotation was carried out in three different parallel chambers to speed up recovery and increase the quality and quantity of nickel products. In addition, the tailings were recycled to be used as feed and any remaining minerals were returned to the source ores.

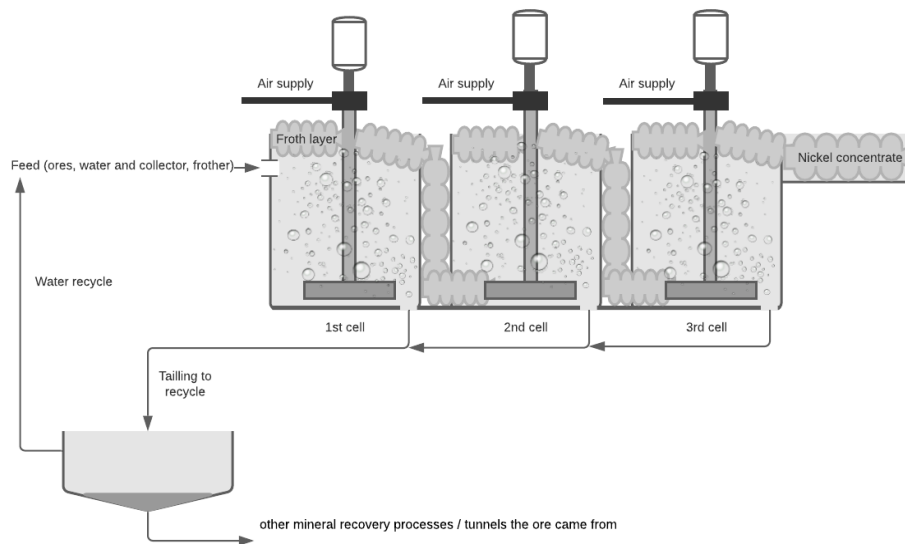


Fig. 1. Process flow diagram of nickel extraction applying natural inventive principles.

2.2 Ecological Feasibility Evaluation of the Proposed Process Design

The ecological feasibility study of the proposed process design (Fig. 1) is based on experimental results. The experiment was carried out on a pilot scale under real operating conditions. The eco-feasibility assessment was focused primarily on the eco-problems presented in Table 1 and took into account all aspects that enable environmental permits, such as strategies to mitigate the specific impacts, environmental regulations, and standards. The results were then compared to current technology. Evaluation criteria and ranking for ecological feasibility assessment are given in Table 3. The final ecological feasibility refers to the average number of assessments of overall environmental impacts.

It is also essential to consider the viability and feasibility of the process design project in the context of sustainable technology development. If this proves to be viable and estimations suggest that the project indicates signs of being ecologically feasible in the future, a broader perspective related to technical and economic aspects must be considered to reach an informed decision.

Table 3. Eco-feasibility ranking criteria.

Ecological feasibility criteria	Ranking	Score
Very low ecological impact, no mitigation of eco-impacts required	Very high feasibility	5
Low ecological impact, minimal and effective mitigation required / possible	High feasibility	4
Moderate ecological impact, minimal and effective mitigation of eco-impact possible	Moderate feasibility	3
Significant ecological impact, limited mitigation of eco-impact possible	Low feasibility	2
High ecological impact, little/no mitigation of eco-impact possible	Very low feasibility	1

A comparative analysis of the ecological assessment and a scored ranking comparison between prior and new process of nickel extraction are presented in Table 4. It can be seen that the application of natural eco-inventive principles in the new technology of froth flotation is rated as ecologically high feasible (low to very low ecological impact) with average score of 4.1 out of 5.

Table 4. Eco-feasibility assessment of a new nickel extraction process based on natural eco-inventive principles compared to the prior technology.

No	Eco-parameters	Prior process	New process (natural principles applied)
1	Energy consumption	2	3
2	Air pollution	1	4
3	Acidification	1	5
4	Safety risks	1	4
5	Chemical waste disposal	1	5
6	Depletion of abiotic resources	1	3
7	Toxicity	1	5
8	Eutrophication	2	4
9	Photochemical oxidation	2	4
10	Ozone layer depletion	2	4
11	Water pollution	1	4
12	Raw material intensity	1	4
13	Solid waste	2	4
Average ecological feasibility score (scale: 1 - very low ... 5 - very high)		1.4 (Very Low)	4.1 (High)

The ecological assessment of the impacts identified for the proposed process design of froth flotation indicates that most of the environmental impacts could be effectively mitigated. All eco-parameters, except for *Energy consumption* and *Depletion of abiotic*

resources, in the nickel extraction operations have a ‘low’ to ‘very low’ ecological impact. The feasibility ranking for eco-parameters of *Energy consumption* and *Depletion of abiotic resources* in the new process technology is slightly lower (moderately feasible) than in the prior process because the ores grinding process here was not directly integrated into the proposed design. However, the overall ecological feasibility scores are deemed ‘feasible’ due to the generally low ecological impacts.

3 Correlations between Natural Eco-Inventive Principles

The analysis of the correlations between the six natural eco-inventive principles A–F implemented in the process design (Table 2) is based on the experimental test of the proposed solution illustrated in Fig. 1 and on the eco-feasibility assessment presented in Table 4. From this it can be determined which combination of inventive principles addresses the most important environmental issues. The relationships between the eco-parameters and natural eco-inventive principles applied here are shown in a correlation matrix in Table 5.

The correlation matrix presents interactions between 13 eco-parameters and contains the most relevant combinations of natural eco-inventive principles to solve primary and secondary eco-problems. This 13x13 correlation matrix is a further development of our previous studies [9, 11] and can be used to select natural eco-inventive principles. For instance, for reduction of (1) *Energy consumption* as a primary eco-problem and avoiding (2) *Air pollution* as a secondary eco-problem the matrix recommends the inventive principles of (D) *Use in parallel different technologies* and (E) *Simultaneous absorption of substances*. A look at other applications of principles D and E for more secondary problems in the first matrix line shows that they would additionally improve the eco-parameter (4) *Safety risks*. In other words, the application of a combination of two natural eco-inventive principles can improve one primary and one or more secondary eco-parameters. In its concept the correlation matrix is similar to the Contradiction Matrix known in TRIZ [6, 7] and can be used for resolving eco-engineering contradictions. The eco-engineering contradiction is defined here as a situation in which the improvement of a primary eco-parameter causes the worsening of a secondary eco-parameter.

The identification of the primary eco-parameters and eco-problems can usually be carried out at the phase of problem definition. Thus, the natural inventive principles can be selected according to the estimated priority of main ecological parameters to be improved. In more sophisticated problem situations, the Importance-Satisfaction Analysis for chemical and process engineering [12] can help to determine environmental parameters to be addressed first. The Importance-Satisfaction Analysis can be also applied for requirement ranking or for the objective identification of the high priority environmental and process intensification problems.

Table 5. Correlations matrix of eco-parameters and applied natural inventive principles (A-F).

Primary eco-parameter to be improved		Secondary eco-parameter to be improved												
		1	2	3	4	5	6	7	8	9	10	11	12	13
1	Energy consumption		D E	D C	D E	D A C	D F	D A B	D A C	D A B	D A B	D C	D A	D C
2	Air pollution	E A		E C	E	E A C	E F	E A B	E A C	E A F	E A F	E C	E A	E C
3	Acidification	C D	C E		C E	C A	C F	C A B	C A	C A B	C A B	C	C A	C
4	Safety risks	E D	E	E C		E A C	E F	E A B	E A C	E A B	E A B	E C	E A	E C
5	Chemical waste disposal	A C D	A C E	A C	A C E		A C F	A C B	A C	A C F	A C B	A C	A C	A C
6	Depletion of abiotic resources	F D	F E	F C	F E	F A C		F A B	F A C	F A B	F A B	F C	F A	F C
7	Toxicity	A B D	A B E	A B C	A B E	A B C	A B E		A B C	A B	A B	A B C	A B	A B C
8	Eutrophication	A C D	A C E	A C	A C E	A C	A C F	A C B		A C B	A C B	A C	A C	A C
9	Photochemical oxidation	A B D	A B E	A B C	A B B	A B C	A B F	A B	A B C		A B	A B C	A B	A B C
10	Ozone layer depletion	A B D	A B E	A B C	A B E	A B C	A B E	A B	A B C	A B		A B C	A B	A B C
11	Water pollution	C D	C E	C	C E	C A	C F	C D B	C A	C A B	C A B		C A	C
12	Raw material intensity	A D	A E	A C	A E	A C	A F	A B	A C	A B	A B	A C		A C
13	Solid waste	C D	C E	C	C E	C A	C F	C A B	C A	C A B	C A B	C	C A	

4 Concluding Remarks and Outlook

Nature provides us with numerous examples of extraordinary properties that far surpass those of current technologies and are relevant to addressing ongoing challenges that require transformative change, such as those related to sustainable development.

Nature's handling of multi-objective optimization under boundary conditions brings a perfect example of chemical process intensification and sustainable process development. The research paper presents an eco-feasibility study of process design using natural eco-inventive principles and analyses the correlations between the inventive principles applied to mitigate the ecological impact. This is an important early-decision point in determining whether the selected technology or process should be implemented.

The paper gives a feasibility assessment example of application of natural eco-inventive principles to the sustainable process design. In accordance with the Nature-Inspired Chemical Engineering approach [1, 8] these natural eco-inventive principles should help to innovate guided by nature but without mimicking nature. The authors advocate a hypothesis that the eco-inventive principles inspired by nature should lead to the sustainable solutions with a lower secondary environmental impact. Therefore, the future research should be focused on systematic identification of new natural inventive principles or sub-principles for eco-innovation, their classification and assignment to the eco-parameters, eco-engineering contradictions and eco-innovation domains under consideration of environmental, technological, and economical requirements.

Table 6 illustrates the current state of research based on literature reviews, our previous [2, 9] and ongoing [13] studies. A comparison to the classical TRIZ inventive principles outlines that some natural eco-inventive principles give a more precise recommendation on how to create sustainable products or processes.

Table 6. Natural eco-innovations principles in progress (fragment).

No	Natural eco-inventive principle	Corresponding TRIZ inventive principle
1	Use in parallel different technologies, for example to block harmful effect [9]	5. Combining
2	Simultaneous absorption of substances from gas / fluid [9]	5. Combining 29. Pneumatics and hydraulics
3	Use different sides or parts of an object for (competing) operations [9]	Separation in space
4	Use natural materials [9]	25. Self-service / Use of resources
5	Utilise waste resources [9]	25. Self-service / Use of resources
6	Use microorganisms [9]	25. Self-service/Use of resources
7	Attract and use bio-resources [9]	25. Self-service/Use of resources
8	Apply biodegradable waste to collect and remove harmful substances [9]	25. Self-service/Use of resources; 22. Converting harm into benefit:
9	Isolate sensitive processes from hostile environment in time and space [9]	3. Local quality Separation in time and space

No	Natural eco-inventive principle	Corresponding TRIZ inventive principle
10	Use non-regular 3D reinforcement structures [9]	4. Asymmetry 17. Shift to another dimension
11	Dynamic equilibrium [14] and force balancing [1]	15. Dynamism and adaptability
12	Dynamic self-organisation and self-adaptability [1]	15. Dynamism and adaptability, 25. Self-service
13	Performing critical process phase in advance (under more favourable conditions)	10. Prior useful action
14	Accumulation of energy or substances in advance	10. Prior useful action
15	Energy harvesting and micro-harvesting	25. Self-service / Use of resources
16	Substance or material harvesting	25. Self-service / Use of resources
17	Use of chemically diverse multi-structure	40. Composite materials
18	Use a variety of resources: rapid, flexible, and reversible resources management	25. Self-service / Use of resources
19	Use the same system to collect and store substance or energy	6. Universality
20	Use large surface with short distance to desirable substance or object	3. Local quality

Furthermore, the proposed eco-feasibility valuation should be compared with other existing approaches to sustainability assessment of technologies in the early phases of product and process development [15]. Moreover, it should be investigated how the natural eco-inventive principles correlate with the modern TRIZ approaches to eco-innovation, for example, presented in [16, 17].

The identification and classification of natural inventive principles in biological systems is a challenging time-consuming task that requires expert knowledge and experience. Therefore, for this purpose, the authors recommend the application of machine learning algorithms and AI-based methods as the subject of future research activities.

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