Sustainable Circular Natural Resource-Based Bioeconomy

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Efficient material flows promote sustainable circular natural resource-based bioeconomy. Within sustainable natural resource utilization carbon and nutrient recycling are financially equal production inputs compared to traditional mineral fertilizers.

Keywords: financial profitability ; forest management ; pulp and paper industry ; pulpwood plantation ; reforestation ; recycled nutrients ; sludge ; sustainability

1. Introduction

The current economic system and related food and other biomass production is based on the linear, inefficient utilization of global resources. One of the main reasons for grand environmental challenges is the incomplete (commercial) valuation of natural resources in terms of the exploitation cost and the full value of products, which leads to the over-exploitation of natural capital [1]. An alternative production model to the existing linear and open-ended bioeconomy systems, namely, a circular bioeconomy, should be based on business renewal and new types of structural and functional solutions through out various value-adding chains covering technological, institutional, and social changes [2].

The role of biobased products is ever increasing due to the exhaustion of non-renewable raw materials. Rockström et al. [3] have defined the safe operating space for human societies through critical planetary boundaries at the global level, and Steffen et al. [4] have completed the work by accounting for the regional-level heterogeneity. Biosphere integrity, i.e., biodiversity loss, and biogeochemical flows, i.e., phosphorus and nutrient cycling, have transgressed their sustainable level most seriously while Land-system change and Climate change, both relating intensively to the carbon cycle, are closing the resilience of the system.

The efficient supply of biomasses requires industrial-scale production systems leading to a variety of environmental problems, including nutrient-induced environmental change [5]. Rockström et al. [3] have estimated that large amounts of nitrogen and phosphorus caused by human processes lead to concern over the global cycles of these two substances, especially nitrogen, which has already exceeded its boundary. The need for nitrogen-based fertilizers in various types of biomass production is one of the major causes for disturbing global cycles, as the annual production converts more than a hundred million tons of N_2 from the atmosphere into new reactive forms, having negative environmental consequences. This conversion is also a very energy intensive process with the use of fossil fuels [6] (Worrell et al., 2000), increasing greenhouse gases and further strengthening climate change. Around 9 million tons of phosphorus, the other key nutrient, ends up in the oceans, speeding up the nitrification of water ecosystems [4][7]. Especially, non-renewable nutrients become even scarcer due to the population growth and consequent increasing volume of fertilizers in food production [8]. Due to the negative environmental impacts and limited availability of non-renewable nutrients, it is relevant and justified to identify the financial and environmental potential of recycled nutrients as compensation of new mineral nutrients.

Sludge is one of organic residues which can be applied a soil amendment and a source of nutrients within agriculture and forestry [9][10]. Sludge from pulping and paper production and the related wastewater treatment also includes nutrients such as nitrogen and phosphorus. Pulp and paper mill (PPM) sludge is generally considered as waste to be disposed of by, for instance, landfilling [11]. However, this type of sludge can be processed into soil improvement material, including recycling nutrients. The sludge can be processed for soil conditioning, incineration, composting, and fertilizing. The PPM waste waters and sludges can be utilized safely as additional nutrient sources to mineral fertilizers and as soil improvement material amendments in agriculture and forest plantation production [12]. The advantages of this type of industrial sludge compared to community-based sludge are its homogeneity and predicable composition [13]. Although sewage sludge contains relatively higher degrees of nutrients [14], it may consist of harmful substances such as heavy metals and pathogens [15].

Furthermore, there is increasing pressure towards indigenous forests, and the consequent decrease in forest area requires actions to offset the negative impacts on ecosystem services at large. The over-logging of indigenous forests can change the ecosystem radically. For example, *Imperata* grasslands followed by over-logged rainforests in South Kalimantan, Indonesia, have no proper value for local communities, and the biodiversity is marginal compared to various forest ecosystems [16]. Deforestation not only has negative environmental impacts, but it can also lead to lower economic and social performance in the surrounding societies, for example, in terms of decreased water quality, lower value and production of various forest-based products, and diminishing working opportunities. Low-value grasslands can be reforested with fast-growing tree species. For example, *Acacia mangium* grows more rapidly than grass in the start-up competition and the wood quality fits well with the current pulp and paper process. After occupying the grassland, the same areas can be rehabilitated with indigenous tree species, leading to higher value and more diverse forests [17][18][19].

Commonly, the soil in the tropics can be relatively poor, and over-logged areas suffer from erosion and related nutrient leaking. Consequently, the establishment of plantations is based on intensive fertilization. In commercial wood production, one option is to replace a part of artificial fertilizers by recycling the nutrients of the industrial wood processing back to wood production. For example, the wastewater of modern PPM is treated with biological wastewater treatment technology that requires nutrients in the process. The purified but nutrient-rich water is led into the water ecosystems. Homogenous and relatively clean wastewater and sludge from pulp and paper processes are applicable additional nutrient sources to mineral fertilizers and soil improvement material in agricultural and forest plantation production. This would close the loop when considering the entire production chain from raw material source, pulpwood, to process, pulp, and paper, promoting the circular bioeconomy (**Figure 1**).

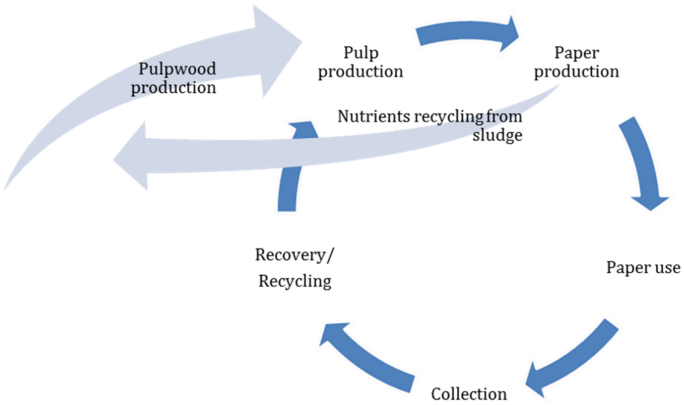

Figure 1. Circular bioeconomy model within pulp and paper production [20].

The increasing demand of both renewable and non-renewable raw material creates the need for new types of industrial-level, environmentally and financially feasible circular bioeconomy models. However, the development process is still on its way. This study completes the knowledge gap related the financially and environmentally feasible business models.

2. Incorporation of the Circular Bioeconomy Model with Sustainability Analysis

This section presents a qualitative analysis with a sustainability perspective regarding the use of recycled nutrients from pulp and paper mill sludge in industrial-scale biomass production. Due to the limited data, the expected benefits are integrated qualitatively into the scenarios. **Figure 8** illustrates a holistic view of the qualitative values in the triple value model.

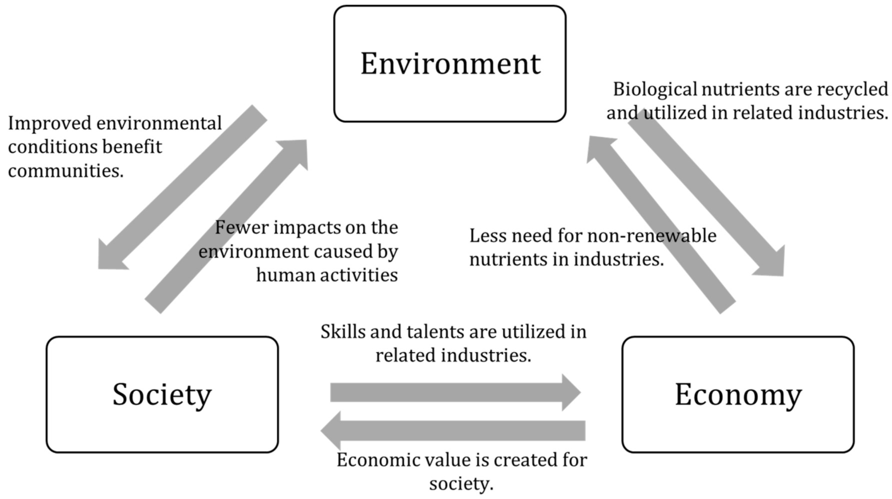

Figure 8. Systems approach to sustainability by the use of recycled nutrients, adjusted according to [21].

Some environmental, social, and economic issues related to the nutrient recycling within biomass production and processing were reviewed qualitatively at local and global level based on previous studies in order to illustrate the total value potential of the Scenarios 2 and, especially, 3 and, hence, the entire circular bioeconomy approach from the social and environmental perspective (**Table 11**).

Table 11. Potential benefits of applying recycled sludge-origin nutrients in biomass production.

	Environment	**Economy**	**Society**	**References**
		Micro (local level)		
Improvement in soil properties	• **Possible to improve soil organic matter and biological processes, soil bulk density and aggregation, soil water holding capacity, cation exchange capacity, and liming benefits**	• Prolong agricultural lands • Possible to increase productivity and consequently financial profitability	• **Better soil quality** ⇨ Improved soil productivity ⇨ Higher financial profitability	[9][22]
Homogeneous and less contaminating sludge properties of sludge	• **Less harmful to aquatic ecosystems and food networks due to leaching and erosion**	• **Simple processes with existing equipment, no need for additional investments in sludge preparation**	• **Fewer risks to people caused by contaminated water**	[23]
Application in rapidly growing plantation	• Low risks of nutrient losses due to the ability of root systems of forest crops to maintain the nutrients in the ecosystem • Allows biological nutrients to circulate through nutrient cycles of the plantation • Supports reforestation and provides consequent benefits regarding carbon sequestration and biodiversity	• Provides commercial wood products • No need to apply sludge frequently due to low demand from fast growing trees; saves cost	• Safe for people, as wood products are not involved in the human food chain • Work opportunities for local people • Industrial economic benefits	[10][16]
		Macro (global level)		

	Environment	Economy	Society	References
Potential as a practice that provides ecosystem services	• Regulating services—air quality and climate regulations through plantation • Supporting services—soil balance by sludge • Carbon sequestration: 1) tree growing, 2) returns sludge-based carbon to soils, 3) growing trees	**• Provisioning services—fiber and fuel (wood products can also serve as an energy source)**	**• Cultural services—cultural diversity and social relations among actors involved**	[24]
Potential as a substitute for mineral fertilizers.	• Reduces greenhouse gases originating from fossil-energy-based technologies in mineral fertilizer production • Mitigates the eutrophication of water ecosystems due to leaking nutrients • Other relevant environmental problems caused by the use and productions of new mineral fertilizers • Promotes resource efficiency and waste recycling • A part of planetary boundary improvement	**• A step towards a circular bioeconomy within pulp and paper industry**	• More job opportunities. • Educates people and encourages sustainable development	**Chapter 1, Figure 1, Figure 7,** [12] [25]

The main expected, positive impacts of the application of recycled nutrients are an improved soil production capacity due to increased nutrients and organic material, decreased leaking of nutrients into water ecosystems and, consequently, better water quality, and the intensified carbon sequestration of the soil. The sludge from the biological treatment as well as the wood fiber containing sludges separated from the pulp and paper processes are homogeneous and cleaner compared to the municipal wastewater. The PPI wastewaters and sludges could be utilized relatively safely, even though some cleaning processes are necessary, as additional nutrient sources to mineral fertilizers and as soil improvement materials amendments in agriculture and forest plantation production. The recycling of carbon and nutrients has positive impacts on the mitigation of climate change, as carbon is sequestrated into soil in addition into the produced biomasses. Similarly, the leaking of nutrients and organic material into the water ecosystems decreases on good quality sites. The recycling of nutrients and carbon are also critical for the soil production capacity [12][25] in terms of more efficient nutrient sequestration by the vegetation whether the biomass is processed as paper, food, or energy.

The positive environmental impacts have commonly positive social reflections at the local level, such as increased and diversified working opportunities for local people and the consequent income sources. Especially, the improve soil quality due to the application of carbon-rich recycled material is expected to increase the harvest level in the long run. The environmental quality and various ecosystem services also improves the quality of life of local populations in terms of air and water quality.

3. Conclusions

Sludge can be recycled as a source of fibers or applied in agriculture and forestry as recycling nutrients within regulatory framework, although these technologies are not yet mature. Moreover, the production system or some other systems within close proximity can utilize sludge as an energy source by incinerating for energy conversion [11]. However, the studied type of sludge is applicable as an additional, recycled fertilizer and soil improvement amendments in the wood production on plantations. This practice is considered highly valuable, as it involves the reduction of non-renewable nutrients which are becoming scarce and causing environmental problems concerning planetary boundaries.

The recycling of sludge promotes general resource efficiency by utilizing valuable particles of masses traditionally classified as waste. In addition, the use of recycled nutrients from pulp and paper integrated into the pulpwood production closes the economic loop that is illustrative of a circular bioeconomy. The model is applicable within other biomass processing industries, such as the bioenergy and food sectors. The business model promotes overall circular bioeconomy approaches.

The analyses resulted in slightly higher financial profitability compared with the original data from the reference study. The hypothetical circular bioeconomy model can be considered feasible regardless of the marginal impact on the financial profitability based on the conservative estimates of the applied parameters showed by the original analyses. The results showed that the financial profitability of biomass production is not sensitive to the plantation establishment and management costs. The profitability depends on the mean annal increment and product price.

The results could be even more promising if the nutrient and carbon recycling were studied simultaneously. It can be hypothesized further that the consideration of both nutrient and carbon recycling could increase direct financial profitability of tree growing compared to the tree growing based on mineral fertilization or the combination of mineral fertilizers and recycled nutrients and, even more, indirect value of ecosystem services, such as improved soil production capacity and water balance as well as mitigation of nutrient leaking to water ecosystems and climate change.

The economic profitability, i.e., the profitability of the national economy at large, beyond the operative financial analysis, of the establishment of a forest plantation on *Imperata* grasslands increases notably when the environmental impacts were considered in the analysis. Especially, the benefits of reforestation of over-logged indigenous forests are economically attractive. Moreover, the qualitative sustainability analysis here showed the holistic values among sustainability approaches and a variety of benefits at both the local and global levels. Consequently, further research is recommendable to assess the concrete impacts and benefits concerning the sustainability of the use of pulp and paper mill sludge to present higher values of this practice. In addition, further interdisciplinary studies on environmental aspects and economic and social approaches should be promoted to more profoundly evaluate the qualitative dimensions, the long-term environmental, economic, and social benefits, and to direct financial profitability.

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