論 文 の 内 容 の 要 旨

論文題目　Environmental and social impact analysis for sustainability assessment -Comparison of mineral and recycled phosphorus fertilizers in Japan-
（サステイナビリティ評価へ向けた環境影響と社会影響の分析-日本のリン肥料におけるリン鉱石とリサイクルリンの比較）

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Phosphorus (P) recycling is critical to meet the growing demand of P fertilizers in modern agriculture. Technically, P can be removed and recovered from municipal wastewater treatment plant (WWTP) through struvite precipitation process and sludge ash leaching process. Currently, there are five full-scaled P recovery facilities in Japan since the first operation in 1997. However, producing the recycled P fertilizers costs more than the conventional mineral P fertilizers due to the investment in the infrastructures and maintenances. Most municipal governments are therefore discouraged from adopting the practice.

The impression of "recycled P is expensive" neglects the externality of P production, i.e. the environmental cost that would otherwise cause by the untreated WWTP's effluent, and the social cost that embedded in the upstream resource acquisition processes. Several recent publications have identified such issues as the key concerns for sustainable P consumption. However, there is a lack of integrated assessment framework to support the P recycling policy. Therefore, this study aims at developing a methodological framework that evaluates the environmental impacts and social impacts of P fertilizers consumption in Japan in product life cycle perspective.

This study consists of two major components: the environmental life cycle assessment (LCA), and the social life cycle assessment (SLCA) of mineral and recycled P fertilizers.

First, to evaluate the environmental performance of P recycling technologies in comparison of conventional mineral P acquisition, an LCA was conducted. I examined the global warming potential (GWP) and the eutrophication potential associated with the production of P fertilizers. Using case studies in Japan, two types of recycled P, struvite (MAP) and hydroxyapatite (HAP), were assessed; two types of mineral P, single super phosphate (SSP) and fused phosphate (FP), were used as references. In fact, the characteristics of the four P fertilizers were different, where MAP and HAP were more resembling to FP as a slow releasing fertilizer. MAP and FP had the advantages of additional nitrogen nutrients. A cradle-to-gate life cycle inventory was conducted. The foreground data for MAP and HAP processes was based on technical reports of P recovery facility in Matsue City and Gifu City respectively, and interviews of two P recovery technology companies. The background data for characterizing greenhouse gases (GHGs) emission and eutrophication were collected from commercial databases, IDEA (domestic) and Ecoinvent v3 (international).

A consequential LCA framework to account for the end-of-life of P fertilizers consumption was proposed. Because by implementing the P recovery processes, conventional treatment of P removal in WWTP, which was necessary to meet the local wastewater standards, can be replaced, thus saving the chemical inputs. The LCA results showed that the GHGs emission for MAP was as low as SSP, while the HAP and FP were high. The eutrophication potential for MAP was negative because net mitigation was achieved by removing P from effluent.

To interpret the results, the GHGs emission and eutrophication potential were translated into monetary unit based on LIME 2 characterization factors. The cost of GHGs was estimated based on damage on agriculture, energy demand, and loss of land. The cost of eutrophication was estimated based on the damage on fishery production in Japan. The results showed that, theoretically, by replacing one kg of FP with MAP a 55.6 JPY can be saved. However, such environmental cost was not being paid in practice.

In short, for environmental friendliness, recycled P fertilizers production was as competitive as mineral P depending on the technological choices and the local wastewater treatment standard. In places where demanding strict treatment of P (often places with existing eutrophication problem), implementation of P recycling policy would be a preferable option.

Next, an SLCA was performed to support the P recycling policy by contrasting the social impacts associated with the consumption of mineral and recycled P fertilizers in Japan. SLCA evaluated the potential impact on stakeholders, including the workers and local communities in respective countries for the production activities, and individual farmers and society for the consumption activities. The methodology was based on the UNEP-SETAC Guideline, and improvement was made to describe the case of P fertilizers better.

An indicator approach was applied to evaluate the social impacts. The model was structured in three layers: social impact categories, social themes, and data indicators (or characterized issues). Each social impact category had multiple social themes, and each social theme was characterized by one or more data indicators. A total of 24 data indicators were selected, which consisted of 15 descriptive general indicators and 9 descriptive specific indicators.

The data for descriptive general indicators, which characterized the social impacts related to generally recognized societal value, were directly collected from Social Hotspots Database (SHDB). The data for descriptive specific indicators, which characterized the social impacts related to P industry specific issues was collected from various literatures and supporting documents in P studies. The selection was based on the input from the P experts in two recent academic conferences and, a P mining site visit in China.

The SLCA results showed that consuming recycled P based fertilizers had significantly less social impacts in overall. The social hotspots activities were the P mining in China and Morocco, and P fertilizer production in China; The social hotspots categories were the labor rights and decent works of workers and the human rights of local communities. By switching to recycled P consumption, farmers in Japan could reduce their social impacts that inherent in the fertilizers. However, in reality, the capacity of recycled P fertilizer production was constrained by the total available P collected in the WWTP. Only 15% of the imported P rock could be substituted in maximum. Therefore, even if the P recycling policy was compulsory, the effects of social impacts mitigation from P fertilizers consumption at nation scale would not be significant.

In conclusion, this research addressed the challenges in evaluating the sustainability of mineral and recycled P fertilizers consumption by proposing systematic frameworks based on life cycle thinking, i.e. LCA and SLCA. The assessment could facilitate future debate on inclusion of environmental and social externalities in P recycling policy making.